TECHNOLOGY FOCUS
टैक्नोलॉजी फोकस

An In-house S&T Bulletin of DRDO

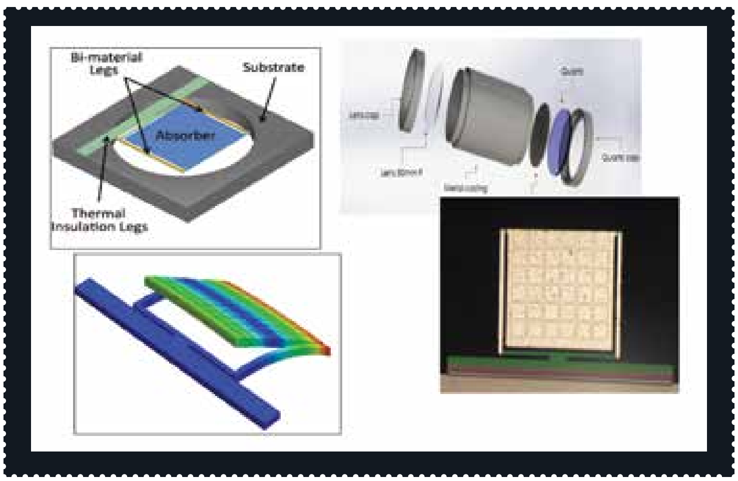
www.drdo.gov.in

Vol 31 | Issue 3 | June 2023 | ISSN No. 0971 - 4413

ADVANCED SEMICONDUCTOR DEVICE TECHNOLOGIES

Technology Focus focuses on the technological achievements in the organization covering the products, processes and technologies.

June 2023
Vol. 31 | Issue 3 | ISSN No. 0971-4413



Laboratory Correspondents

Agra	:	Shri SM Jain, ADRDE
Ahmednagar	:	Col Atul Apte, Shri RA Shaikh, VRDE
Ambernath	:	Dr Ganesh S. Dhole, NMRL
Bengaluru	:	Shri Satpal Singh Tomar, ADE
	:	Smt MR Bhuvaneswari, CABS
	:	Smt Faheema AGJ, CAIR
	:	Shri R Kamalakannan, CEMILAC
	:	Dr Sanchita Sil & Dr Sudhir S Kamble, DEBEL
	:	Dr V Senthil, GTRE
	:	Dr Sushant Chhatre, MTRDC
Chandigarh	:	Dr Pal Dinesh Kumar, TBRL
	:	Dr Anuja Kumari, DGRE
Chennai	:	Shri K Anbazhagan, CVRDE
Dehradun	:	Shri Abhai Mishra, DEAL
	:	Dr SK Mishra, IRDE
Delhi	:	Shri Sumit Kumar, CFEES
	:	Dr Dipti Prasad, DIPAS
	:	Shri Santosh Kumar Choudhury, DIPR
	:	Shri Navin Soni, INMAS
	:	Shri Anurag Pathak, ISSA
	:	Dr Rupesh Kumar Chaubey, SSPL
Gwalior	:	Dr AK Goel, DRDE
Haldwani	:	Dr Atul Grover, DIBER
	:	Dr Ranjit Singh
Hyderabad	:	Shri ARC Murthy, DLRL
	:	Dr Manoj Kumar Jain, DMRL
Jodhpur	:	Shri DK Tripathi, DL
Kanpur	:	Dr Mohit Katiyar, DMSRDE
Kochi	:	Smt Letha MM, NPOL
Leh	:	Dr Tsering Stobden, DIHAR
Mysuru	:	Dr M Palmurugan, DFRL
Pune	:	Dr Ganesh Shankar Dombe, HEMRL
	:	Shri AK Pandey, ARDE
	:	Dr Anoop Anand, R&DE(E)
Tezpur	:	Dr Sibnarayan Datta, DRL

Readers may send their suggestions to

The Editor, Technology Focus
DESIDOC, Metcalfe House
Delhi-110 054
Telephone: 011-23902403, 23902472
Fax: 011-23819151; 011-23813465
E-mail: director.desidoc@gov.in; techfocus.desidoc@gov.in; technologyfocus@desidoc.deldom
https://www.drdo.gov.in/technology-focus

From the Desk of Guest Editor

The Microelectronic components fabricated on semiconductor materials termed as microelectronic semiconductor devices are the building blocks of strategic systems. Solid State Physics Laboratory (SSPL), Delhi exploits its expertise to develop critical semiconductor device technologies denied to India.

This issue of technology focus namely 'Advanced Semiconductor Device Technologies' is sequel to the earlier issue 'Advanced Semiconductor Material Technologies' and covers device technologies developed at SSPL for mmW, IR, visible, and THz regions of the electromagnetic spectrum.

The indigenous development of various compound semiconductor technologies at SSPL includes Gallium Nitride (GaN)-based Monolithic Microwave Integrated Circuits (MMICs) for application in Radars, Electronic Warfare, Jammers, EM Seekers and Remote Imagers. The MMICs fabricated are Power Amplifiers (PA), Low-noise Amplifiers (LNA), Single Pole Double Throw Switches (SPDT) and Transreceiver chips based on the indigenous GaN technology. The epitaxial material used for these products is also developed at SSPL. Single Emitter Semiconductor Laser diodes based on GaN and Gallium Arsenide (GaAs) technologies are also indigenously developed for application as seed lasers for Directed Energy Weapons (DEW), explosive detonation, and underwater communication.

The indigenous technologies of GaN MMIC, GaAs and GaN-based laser diodes have been established for production in GAETEC. IR Sensors is the heart of IR imagers ranging over Short Wave IR (SWIR), Medium Wave IR (MWIR), and Long Wave IR (LWIR). As brought out in the previous issue, SSPL has achieved self-reliance in IR material development and while all the peripheral technologies leading to IR images are already in production, *the IR sensor technology based on MCT, T2SL, and Si MEMS are at a mature stage of development. The Dewar to house the sensors and Sterling Cooler to hold the DEWAR at cryogenic temperatures have been transferred to production. Si Read Out Integrated Circuit (ROIC) is under production in SCL, Chandigarh.*

Sensors for safe and arm devices, CBRN and snow avalanche prediction have been developed and transferred for production to industry. Quantum and THz are emerging technologies that are also being pursued for futuristic applications in sensors, imaging and computing at SSPL. GAETEC & STARC are the pilot production FAB foundries that not only absorb the technologies developed at SSPL but also hold a symbolic partnership with SSPL in the very establishment invigilation.

For easy understanding of the readers, this issue is focusing on device concepts in simple terms including fabrication processes. The devices and circuits developed by SSPL have already been successfully implemented in a variety of defence and space missions. I am sure, that this issue will allow readers to obtain up-to-date information about emerging trends and future directions of essential critical semiconductor device technologies. Key articles in each section present snap-shot and mini reviews of state-of-the-art inhouse results making the issue a must read for engineers, scientists, and students working on development of advanced and futuristic device technologies.

Dr Seema Vinayak
OS & Director, SSPL

ADVANCED SEMICONDUCTOR DEVICE TECHNOLOGIES

Semiconductor devices are the essential components to bridge the gap from material to any specific application. Solid State Physics Laboratory (SSPL) works on a variety of device technologies critical to civil/defence applications. The main focus is to develop innovative device solutions with a strong focus on compound semiconductor device technologies for RF, photonics, and IR detector applications. This includes novel device concepts both on semiconducting materials like GaAs, GaN, and HgCdTe and on related materials providing a 'technology-push' towards new and more powerful applications critical to countries strategic requirements.

SSPL covers activities from GaAs/GaN High Electron Mobility Transistor (HEMT)-based Microwave Monolithic Integrated Circuits (MMICs), Laser Diodes and SWIIR/MWIR Focal Plane Arrays (FPAs) design/development and their integration for specific applications as well as advanced futuristic semiconductor devices.

SSPL developed devices and circuits are implemented in a variety of defence and space missions. SSPL pays special attention to R&D on semiconductor device technologies not available easily from outside and essential for meeting demanding strategic domestic requirements. This chapter mainly focuses on device technologies including fabrication processes developed in-house covering from GaAs MESFET/HEMT-based MMICs, GaN HEMT-based MMICs, Laser Diodes and InGaAs uncooled/HgCdTe cooled IR FPA's.

Indigenous Gallium Nitride MMIC Technology

Gallium Nitride (GaN)-based High Electron Mobility Transistor (HEMT) technology is revolutionising the modern defence RF and electronic warfare systems. This technology has the capability to deliver high power at high frequency with high linearity and high efficiency. Due to these advantages, it is finding use in wide variety of applications such as radar, satellite communication, and military ground communication. GaN-based HEMT technology offers a significant advantage over the existing Gallium Arsenide (GaAs) Monolithic Microwave Integrated Circuits (MMIC) particularly for RF power applications. This is primarily due to the capability of GaN devices to operate at higher voltages owing to very high breakdown fields associated with them. Additionally, the GaN devices offer much higher impedance resulting in the requirement of less complex matching networks in RF power amplifier integrated circuits. On the whole, GaN technology results in minimising the size of RF ICs by a factor of ten or even higher over the competing RF technologies. Moreover, the low current operation aided with a higher efficiency results in power saving and reduced cost for cooling the system. Therefore the GaN-based power amplifiers constitute the heart of present day transceiver (T/R) modules in Active Electronically Scanned Array (AESA) radars and communication systems.

SSPL has developed indigenous AlGaN/GaN power HEMT material and device fabrication technologies for achieving long term self-reliance in GaN-based material, high power devices, and MMICs for RF applications. This involved the evolution of process control and characterisation methodologies for (i) epi-wafer growth (ii) device simulation (iii) device fabrication, and (iv) DC, RF and load pull measurement of high power devices. Based on a continuous learning process and incremental improvement in understanding leading to process maturity, successful demonstration of depletion mode AlGaN/GaN HEMTs with operability up to

50V drain bias and power densities of ~10 W/mm in S/C band, 5 W/mm in X-band has been attained. Recently, SSPL also demonstrated HEMT devices with power density of 3.5 W/mm at Ku band.

Based on indigenous process, SSPL developed and released GaN PDK for designing MMICs working upto X-band. This PDK has been used for designing high power discrete bars including 130 W S-band high power devices as well as GaN MMICs likes C, and X-band power amplifiers, low-noise amplifiers, and switch circuits.

GaN HEMT Device Process Technology

The HEMT fabrication involves a large number of unit processes that need to be integrated to realise the device with desired reliable reproducible performance. SSPL has developed all the processes required for the fabrication of AlGaN/GaN HEMTs namely, ohmic and Schottky contacts, surface passivation, e-beam lithography, RIE for device isolation and gate slit etching, implant isolation, inter-connect formation by lift-off and electroplating. Devices with gate length of 0.4 µm and 0.25 µm with cut-off frequencies of 26 GHz and 34 GHz, respectively, have been fabricated. To achieve the maximum performance of a particular GaN HEMT, the features that hold the maximum importance are high off-state breakdown voltage, current collapse suppression, low gate and buffer leakage and low on state resistance. Optimisation of these features through simulations, process technology development and characterisation has been achieved at SSPL. The processes have been integrated on indigenously grown material by MOCVD and MBE as well as on imported material. The main technology breakthroughs include the control over breakdown voltage and minimised knee walkout after device surface passivation. Field plates have been incorporated over the gates to improve the device breakdown voltage. The technology has been developed on 75 mm AlGaN/GaN on SiC substrates (Figure 1).

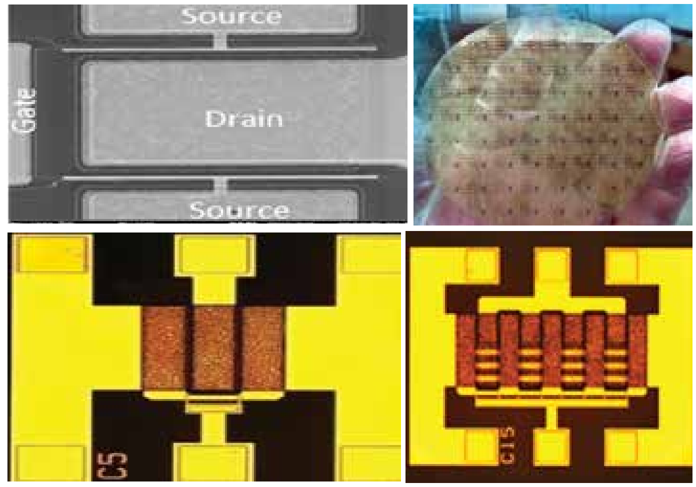


Fig 1. Devices Fabricated at SSPL on GaN/AlGaN Heterostructures on 75 mm SiC Substrate

Depletion mode HEMT devices with 1 A/mm peak drain current density, DC trans-conductance of ~230 mS/mm and extrapolated power output of 5. 0-6.0 W/mm up to X-band have been achieved at 28 V operation. The main process parameters are shown in Table 1.

Table 1. Process Parameters

Unit Process	Attained Results
Mesa isolation by RIE/ Implant isolation with mesa to mesa leakage	~40 nA@ 100 V
Repeatable ohmic contacts with FOM	0.3-0.6 ohm-mm
Schottky contacts with repeatable V_f	0.9-1.2 V@ 1 mA/mm
Reverse Schottky breakdown	-80 V @ 1 mA/mm
Surface Passivation by PECVD and ICPCVD	Minimal knee walkout. Minimal current collapse

Packaged devices with gate width of 7.2 mm have been measured with saturated output power of 30 W in S-band at 3 GHz. The in-house developed bias tees have enabled the on-wafer load pull measurement of large periphery devices. 3 mm devices with fish bone configuration could be measured in a wafer mode with saturated output power of 15 W (Figure 2).

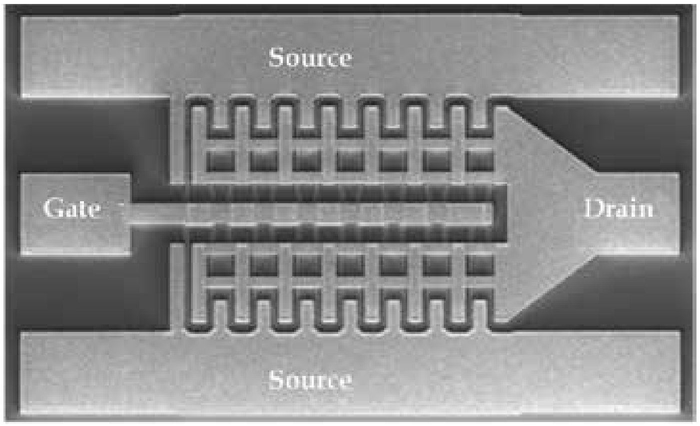


Fig 2 (a). FESEM image of 30 finger 3 mm GaN HEMT Device fabricated at SSPL on GaN/AlGaN Heterostructure on SiC

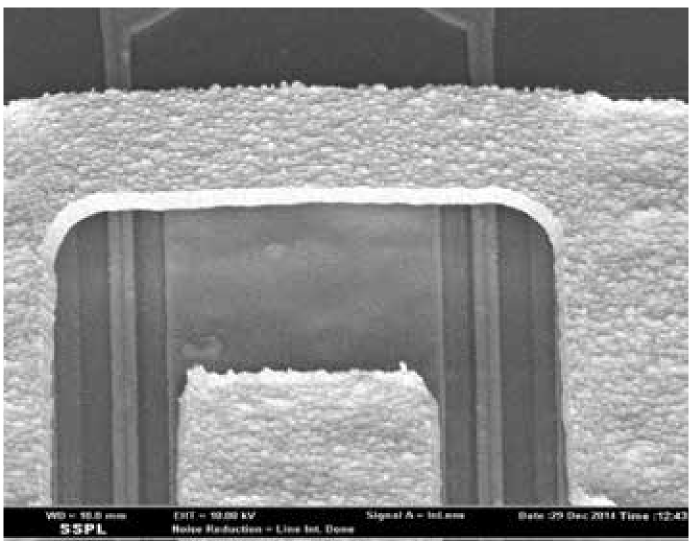


Fig 2 (b). FESEM Image of Air-bridge Connection between Two Source Pads in GaN HEMT Device Substrate

Concurrently, the GaN device fabrication technology is being implemented at GAETEC, Hyderabad to create a production facility for GaN products, thereby making the country self-reliant in GaN MMIC technology.

MMIC-Enabling Technology for Next Generation RF Systems

The GaN HEMTs can either be used as discrete active devices in hybrid RF Microwave Integrated Circuit (MIC) modules or in combination with other passive elements on AlGaN/GaN wafer to form MMICs. (Figure 3)

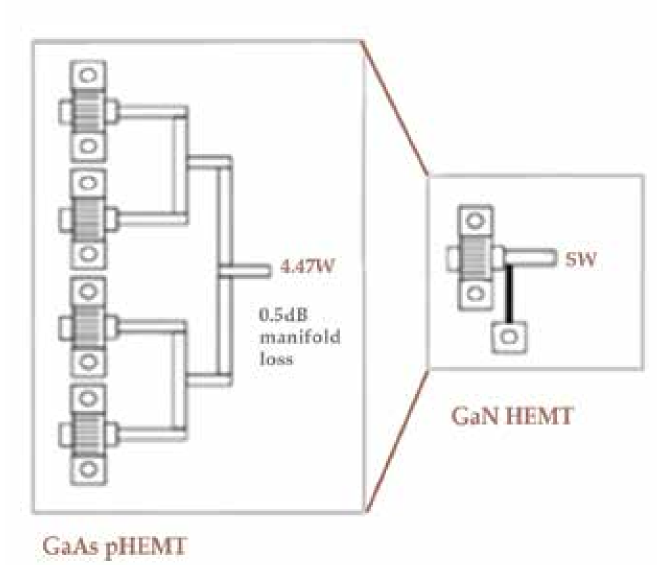


Fig 3. Comparison of Device Geometry for Same Power in GaAs vs GaN

SSPL has demonstrated indigenous GaN-based MMIC technology and developed GaN-based MMICs including power amplifiers, low-noise amplifiers, and RF switch with applications upto X-band. As an important step in designing GaN-based MMICs is a library of passive components (inductor, capacitor, GaN, & NiCr resistors) and active components have been designed and modeled. SSPL has formulated the complete process to integrate the fabrication of passive components with active devices for MMIC realization and demonstrated PA, LNA, and switch MMICs upto x-band. (Figure 4)

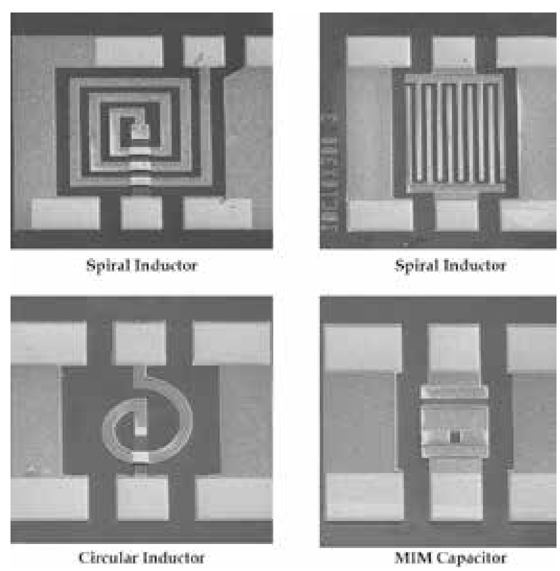


Fig 4. FESEM Image of Fabricated Passive Components with Air Bridge Technology

The via-hole interconnection technology is very important for AlGaN/GaN HEMT devices at microwave frequencies. These structures help in parasitic reduction at higher frequencies. SSPL has developed in-house via-hole technology and implemented in the AlGaN/GaN HEMT-based devices/MMICs on SiC substrate for source grounding. The back-side image of fabricated device with via source grounds is shown in the Figure 5. All the active and passive components have been fabricated with vias.

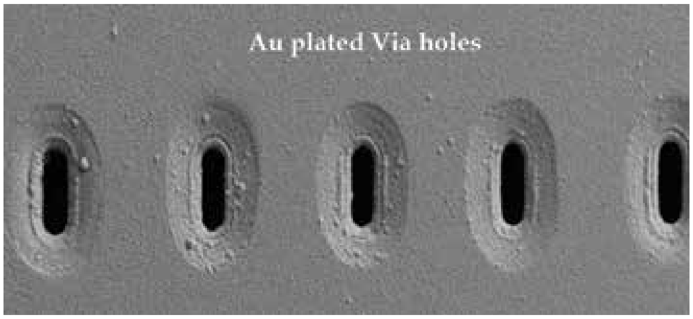


Fig 5. FESEM Image of Back-side via-hole Fabricated on GaN HEMT

GaN High Power Modules

Using the indigenously fabricated GaN HEMT devices a CW linear 10 Watt MIC power amplifier module has been designed at SSPL for frequency range of 1.7-2.1 GHz. The power amplifier has demonstrated small signal gain of 45 dB and 3rd order IMD better than 35 dBc. Assembly of the PA module has been carried out at GAETEC. This task is a step towards complete indigenisation. The module photograph is shown in Figure 6. The measured RF performance of developed PA module is shown in Figure 7 (a) and Figure 7 (b).

Fig 6. CW 10 W Linear Power Amplifier

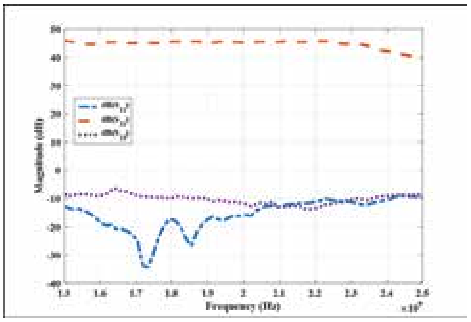


Fig 7 (a). Small Signal Performance of Power Amplifier

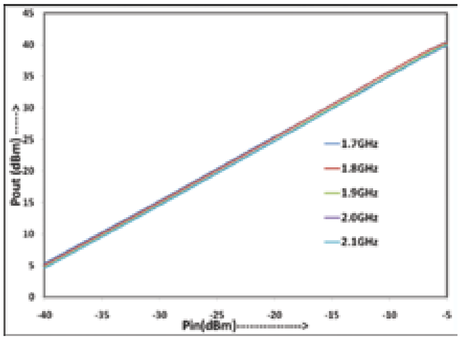


Fig 7 (b). Output of the Power Amplifier

130 W S-band GaN HEMT power bars have also been successfully developed with GAETEC and a private partner. 1000 packaged discrete power devices developed and delivered to Electronics and Radar Development Establishment (LRDE). The packaged devices as shown in Figure 8 are meeting all the specifications over the desired frequency band of 3.1-3.5 GHz.

Fig 8. Packaged 130 W GaN HEMT Device

SSPL along with development partner has designed and developed GaN-based CW 1KW UHF high power amplifier unit. It has been successfully integrated in tele-command system at Integrated Test Range (ITR), Balasore which is meeting all the required user specifications. Till now the similar systems were being imported.

GaN MMICs Power Amplifiers, Low-noise Amplifiers, Switches and TR Chips

GaN HEMT-based C and X band power amplifier MMICs low noise amplifiers and switch circuits have been successfully developed (based on external PDK) and demonstrated. GaN MMIC power amplifiers in C band (5.4-5.9 GHz) with 40 W Pout and X band (9-10 GHz) with 13 W, 20 W, and 30 W Pout using UMS PDK have been designed, fabricated, and characterised. The team demonstrated GaN-based 10 W C-Ku band and 10 W Ku band high power amplifiers, low noise amplifiers, and switch MMIC, which are required in huge numbers for the development of next generation electronic warfare and seeker applications. (Figure 9)

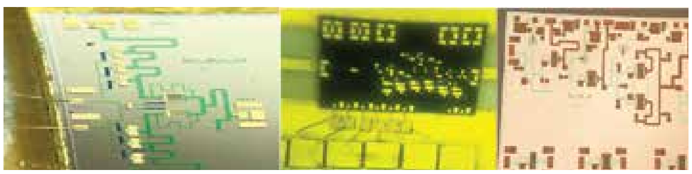


Fig 9. Ku band Switch, LNA and Power Amplifiers

For radar applications, indigenous S band 130 W and X band MMICs including power amplifier, low noise amplifiers, and have been designed, fabricated and tested meeting designed specifications. (Figure 10)

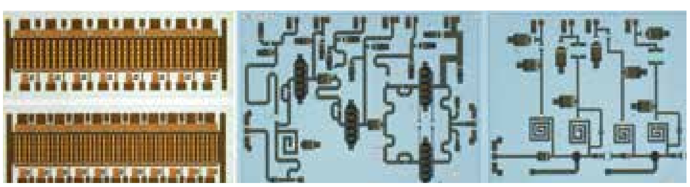


Fig 10. (a) 130 W Power Bar (b) Power Amplifier (c) Low Noise Amplifier

Looking at the present requirements of future electronic warfare systems and radars, GaN has turned out to be the technology-of-choice for RF electronics. Therefore, establishing commercially viable GaN material and MMIC technology is an important goal that SSPL and GAETEC are determined to meet. This is SSPL's contribution towards self-reliance in GaN technology for meeting all the future requirements of strategic systems.

IRFPA

Sensing beyond the human capability has been very useful and attractive for exploring the nature and developing capabilities of controlling and making use of natural phenomenon for the betterment of mankind. In the history of mankind, several efforts have been made in this direction and a number of different kinds of sensors have been developed that aid the human sensing. The infrared sensors are some of those that provide the capability of seeing the wavelengths higher than the wavelength band that can be sensed by the biological eyes of human beings.

Infrared systems are used in numerous applications ranging from defence, space, law enforcement, thermographic inspections, astronomers, and many more. IR imaging enables seeing in dark as it senses the thermal energy emitted by the scene/objects themselves. This also ensures passive imaging which is very important for defence applications to avoid detection by enemy. Another important feature of IR imaging is visibility in fog, dust, and smoke as IR radiation can penetrate through them. They are used in missions ranging from surveillance to high performance target search, track, acquisition and guidance. High performance infrared sensors are the most important elements of the night vision technology. The emerging trends in the battlefield scenario, threat perception, low intensity conflicts/counter insurgency have led to the rapid technological advancement in the development of Infrared Focal Plane Arrays (IRFPAs) consisting of a 2-D staring array of micro-size infrared sensors which is placed at the focal plane of optics in a thermal imaging camera. IRFPAs allow operating in day & night.

Cooled thermal imaging cameras are the most sensitive type of cameras to differentiate small differences in scene temperature. They are the ones that are preferred during war scenarios or military environments. They can detect the smallest of temperature differences between objects. Enhanced performance limits and reduction in cost desired by the users for infrared surveillance, night vision cameras, thermal imaging in medical diagnosis, etc. call for continuous research & development in this vital field. Hence continuous improvement in material quality, detector technology and associated electronics is required for realising the desired performance with lower cost. Uncooled IRFPAs are less sensitive and slower than high performance cooled ones. They are, however, generally, much less expensive and have lower SWaP, i.e., size, weight, and power requirements than the cooled IRFPAs. These sensors can be manufactured in fewer steps with higher yields. They require less expensive vacuum packaging as they do not require cryocoolers, which are very costly devices and deteriorate the long time reliability of cooled IRFPAs. They tend to have much longer service lives under similar operating conditions. Security applications often require continuous operation of cameras to avoid the possibility of missing any threats. IR imaging markets are seeing continuously increasing demands in cooled and uncooled sensor segments.

SSPL is working on development of both cooled and uncooled IRFPAs for past several years. IRFPAs, a major thrust area of the laboratory, involves state of art technology from material development to final integrated device.

SWIR FPA

Short Wave Infra-red (SWIR), nominally 1-3 µm wavelength range, lies between the visible (VIS, 0.4-0.8 µm band of wavelengths) and the Mid-Wave Infra-Red (MWIR, 3-5 µm band of wavelengths) region of electromagnetic spectrum and therefore, enjoys the benefits of both. On one hand, wavelength being shorter than MWIR, it provides better resolution than that provided by MWIR. On the other hand longer wavelength of SWIR compared to VIS gives better atmospheric transmission. Another advantage of SWIR over MWIR is the use of reflected light for imaging rather than emissive picture, which supports improved identification capabilities (Friend-or-Foe identification in war scenario) with active source or night glow. Therefore, imaging in the SWIR can bring useful contrast to situations and applications where visible or MW/LW IR thermal imaging cameras are ineffective. There is a huge requirement of these detectors for variety of defence and civilian applications including night vision using night glow, Laser range finder, 3D imaging, hyper-spectral imaging, wafer inspection and various other astronomical applications, etc. Out of various potential material systems suitable for SWIR imaging, the ability of InGaAs photodiodes to operate at room temperature with high quantum efficiency for wavelengths from 920 nm to 1700 nm (that may be extended to the band of 500 nm to 2800 nm wavelengths also) makes it an optimal material of choice for SWIR imaging applications.

Two dimensional image sensor array kept at the focal plane of the optics is called Focal Plane Array (FPA). These FPAs are usually fabricated by hybridizing two chips, one containing the detector array of desired format and other one containing the signal processing circuitry to collect the detected signals from all individual detector elements of detector array. The two chips, i.e., detector array chip and readout chip are joined together using Indium bumps using flip chip process. For SWIR detectors, InGaAs is the suitable material, while Si is the only material suitable for realising high performance mixed signal VLSI circuits. Therefore, the InGaAs photo-detector array is integrated with Si Readout Integrated Circuit (ROIC) for realising SWIR FPAs as shown in Figure 11.

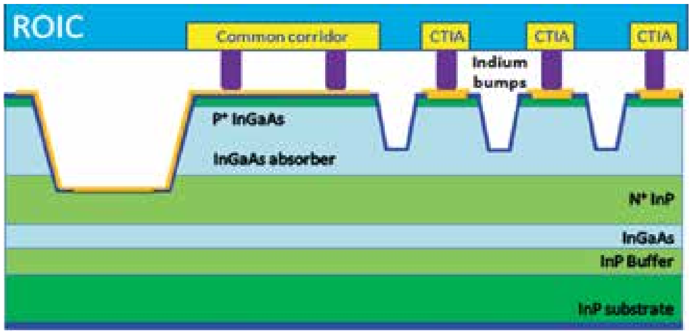


Fig 11. Schematic Cross-section of InGaAs-based SWIR FPA

SSPL has recently developed technology of fabricating SWIR FPAs using semiconductor process technology to form p-i-n detector array of InGaAs/InP and demonstrated the SWIR imaging capability. It includes mesa etching, passivation, contact metallisation, flip chip bonding of the detector array with ROIC chip using indium bumps, back side substrate polishing, development of hermetically sealed High Temperature Co-fired Ceramic (HTCC) package and Thermoelectric Cooler (TEC) after a detailed design for mesa structured detector array along with complete process design prepared in-house for minimum dark current and maximum photo-response for near zero bias operation. Each unit process is under optimisation for effective repeatability, reliability, and yield improvement.

The detector array was designed using 2D and 3D numerical simulations in industry standard ATLAS device simulator as shown in Figure 12. Figure 12 (a) shows the 3D model of 5×5 mini detector array. The central pixel was simulated with incident SWIR flux and the photo generated carriers were investigated in 2D cut-plane as shown in Figure 12 (b).

In the developed process, the p-i-n photodiodes were fabricated on lattice matched In0.53Ga0.47As epi-layer grown on InP substrate by creating mesas

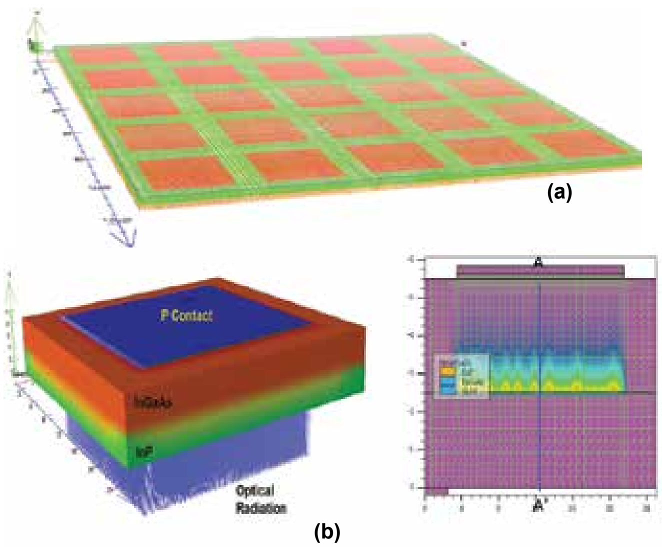


Fig 12. 3D Model of 5×5 Mini Detector Array

for electrical and optical separation among detector pixels which were passivated using a Si3N4 passivation layer. The contact pads were opened in the passivation layer and the p+ contacts from the photodiodes are taken from p+ InGaAs on the mesa. The n+ common contact was taken using a deep trench that reaches down to the n+ InP layer. The common contact, actually taken from the trench bottom, is risen up to a level of the array diode contacts to suite the flip-chip hybridization process. The p+ side of each individual photodiode is connected to the ROIC unit cells, which is mostly a Capacitive Trans-Impedance Amplifier (CTIA). The n+ common contact is connected to the common connection ring of ROIC using indium bumps. The photographs of certain sections of the detector array are shown in Figure 13 after individual process steps.

The performance of the detector elements and the test structures have been evaluated by measuring

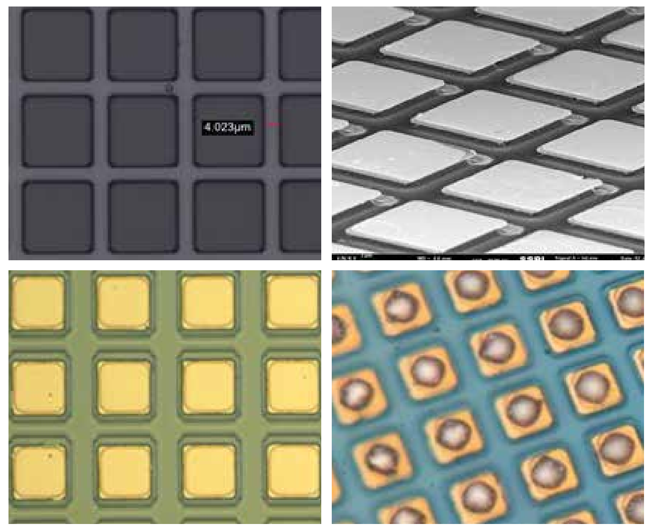


Fig 13 (a) Photographs of the Sections of Detector Array after Mesa Etching, (b) SEM Pictures after Mesa Etching, (c) Photogrpagh after Metallisation, (d) Photograpgh after Indium Bump Growth

terminal electrical characteristics and extracting the characteristic performance parameters. (Fig 14)

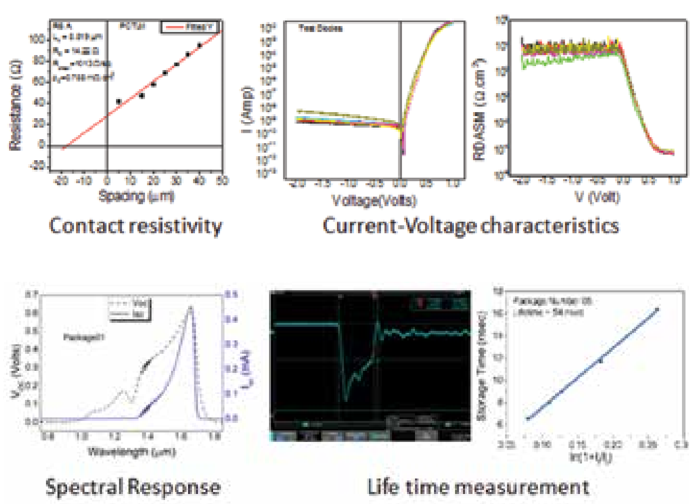
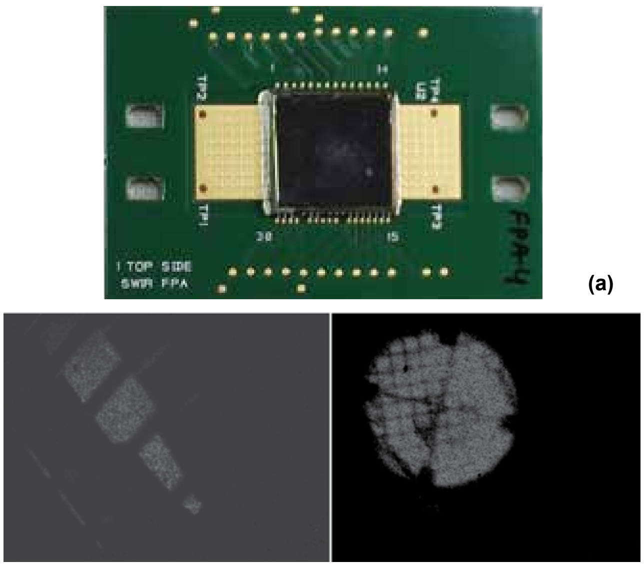


Fig 14. Results of Various Measurements on Detector Elements and Test Structures

The SWIR FPAs have been tested for their radiometric response at Space Application Center (SAC), ISRO, Ahmedabad by bonding them in Chip-on-Board (CoB) PCB as shown in Figure 15 (a). After showing good response to the SWIR flux, these FPAs have also shown good SWIR image of the objects when focussed on to them using SWIR optics. The images of the hot object, such as soldering iron and the hot air blower are shown in Figure 15 (b).



(a)

(b)

Fig 15. (a) The SWIR FPA Mounted on CoB PCB, (b) The Images of Soldering Iron and Hot Air Blower Obtained with SWIR FPAs

MWIR/LWIR FPA

Cooled cameras are generally designed to work in the Long-wave Infrared (LWIR) or the Mid-wave Infrared (MWIR) band. IRFPAs used in a modern cooled thermal imaging camera are housed in a high tech package called 'Dewar' and integrated with a cryocooler that lowers the sensor temperature to cryogenic temperatures. This reduction in sensor temperature is necessary to reduce thermally-induced noise to a level below that of the signal from the scene being imaged. High performing IRFPAs require a complex technology involving a number of sub-technologies and process integrations and has been developed by only a very handful of advanced countries like USA, France, Israel and UK. Most of these technologies are strategic in nature. SSPL is working on HgCdTe-based cooled IRFPAs. IRFPA consist of two dimensional Photovoltaic (PV) infrared detector array fabricated on a thin (~10µm) HgCdTe layer grow on a lattice matched CdZnTe (CZT) substrate, hybridized to Read-Out Integrated Circuit (ROIC) and packaged in a suitable Dewar assembly, integrated to a cryo-cooler. IRFPA technology involves several sub-technologies, like growth of CdZnTe (CZT) substrates, growth of HgCdTe epilayers on these substrates, fabrication of photodiode arrays, design and development of compatible CMOS ROIC, flip chip hybridization of the detector array and the ROIC resulting in the Sensor Chip Assembly (SCA), development of tactical Dewar and JT (Joule-Thomson) cooler and final integration of SCA, Dewar and cooler called as Detector-Dewar Cooler assembly (DDCA). SSPL has developed all of these sub-technologies at laboratory level for MW IRFPA format 320x256/30 µm as well as 384x288/15 µm, 640x512/15 µm and demonstrated thermal images of human target.

Under the strategic material development programme for IRFPA technologies, bulk crystals of semiconducting materials, e.g CZT (Cadmium Zinc Telluride, Zn = ~ 4%), Ge (Sb doped Germanium) and epitaxial layers MCT (Mercury Cadmium Telluride) are grown and fabricated into required sizes and quality. Over the years, several technological achievements, breakthroughs and product development has taken place in these niche areas. Details of these have already been covered under 'Advanced Material' (Vol 31 Issue 2, April 2023).

Fabrication of two-dimensional detector array involves a number of process steps, like surface preparation, surface passivation, photolithography, ion implantation, wet etching, dry etching, & metallization to be done on HgCdTe epilayers. Each of these steps are crucial to obtain desired sensitivity of IRFPA. These process steps are developed under the constraint of damage prone nature of HgCdTe as well as thermal constraint and qualified using process control monitors at SSPL. Detector array testing is done in a cryo-prober that brings detector temperature to 80K during testing. The SSPL's developed indigenous ROIC is a 320×256 array for an 'n on p' type HgCdTe photodiodes, i.e., it is designed to integrate the electrons. One off the shelf ROIC for

640x512 array has also been procured, along with the development of 384x288 ROIC in collaboration with SCL, Chandigarh. Test setups for testing of ROICs at SSPL have been established. To realise a hybrid focal plane array ROIC and detector arrays are flip chip bonded through indium bumps that are grown both on detector array and ROIC chip. Since two different materials are being joined, temperature cycling from room temperature to detector operating temperature, i.e., 80K, will result in a shift in alignment.

In general, the detector array will contract more than the silicon ROIC by an amount that can be calculated from the known thermal expansion coefficients. Technology to grow indium bumps and flip chip bonding process has been developed such that these hybrid arrays can withstand large numbers of temperature cycles. An all metal Dewar suitable for packaging IRFPAs has been developed that involves design and assembly of various components like, HTCC feed-through, detector carrier/header, cold shield, inner Dewar tube, evacuation tube etc., followed by integration, degassing and vacuum sealing of Dewars. SSPL is competent to design Dewar components and seal it with leak rate < 10^{-12} Std. cc/s. Since high performance MWIR detectors work at cryogenic temperatures, SSPL has also developed cryogenic coolers for IRFPAs.

Various equipment are installed to establish these technologies for 320x256/30µm, 640x512/15µm, and 384x288/15µm MWIR FPAs at laboratory level. Images of some of these equipment installed at SSPL are shown in Figure 16.

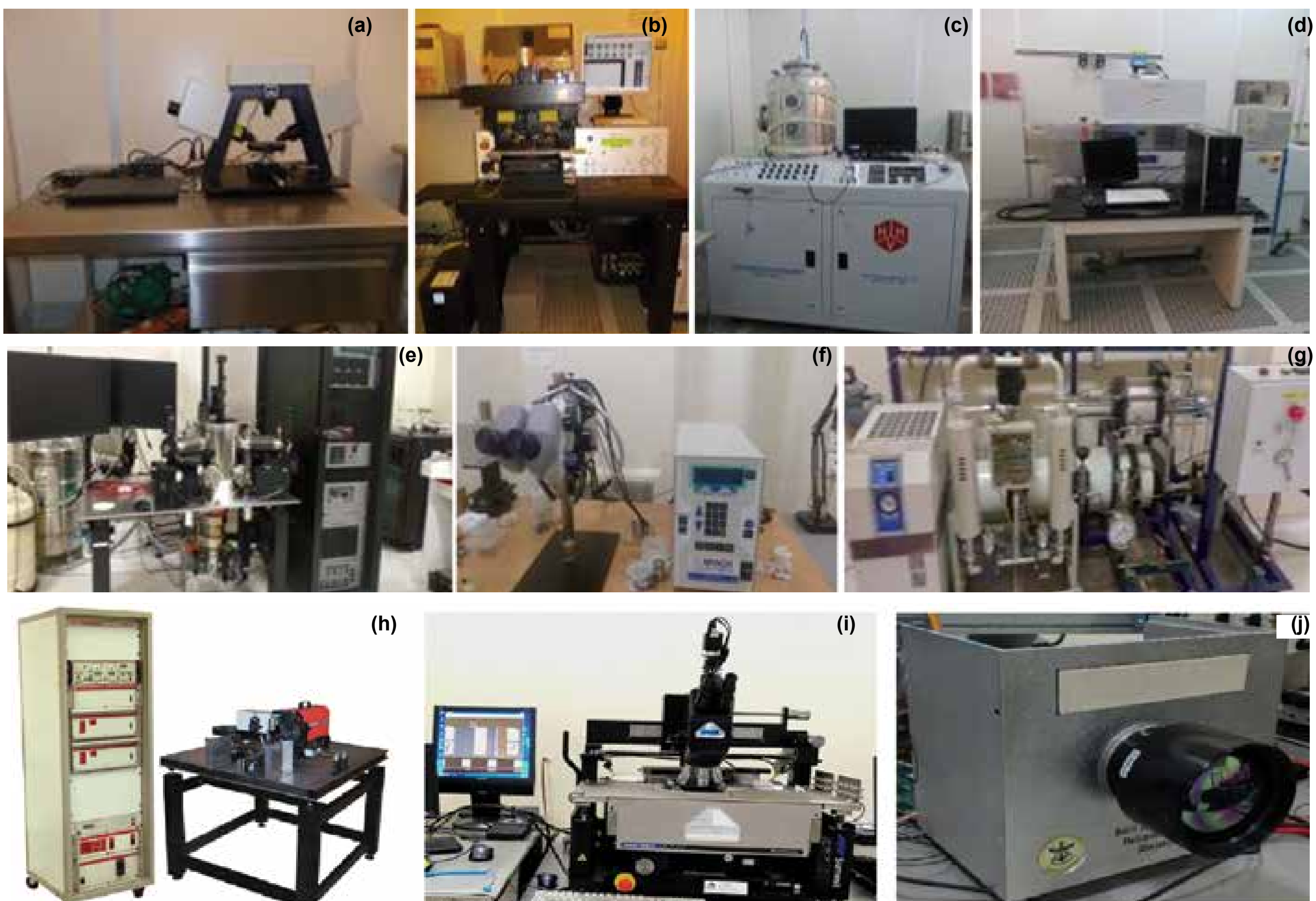
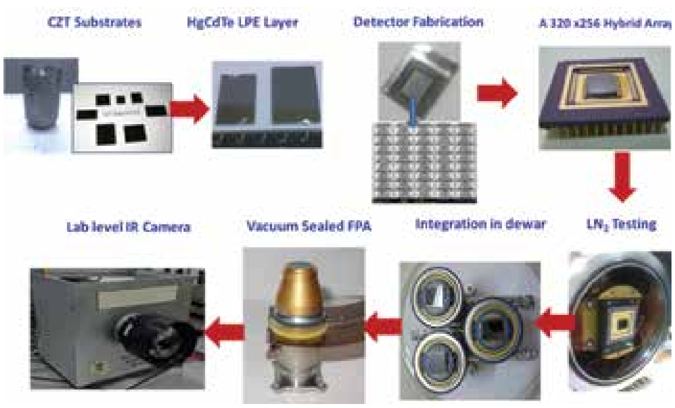


Fig 16. Showing Equipment (a) Ellipsometer for HgCdTe Surface Characterization, (b) Mask Aligner for Photolithography, (c) Vacuum Coating Unit for Passivation & Metallization, (d) ICP RIE for Dry Etching, (e) Cryoprober for Detector Array Testing at 80 K, (f) Parallel Gap Welding for Electrical Connection with Feedthrough, (g) UHV for Ultra High Vacuum Sealing of Dewar, (h) FPA Tester, (i) Wafer Prober, (j) Indigenously Developed Lab Level IR Camera

Figure of merit for these detectors is Noise Equivalent Temperature Difference (NETD) that represents the minimum temperature difference that produces the signal in the detector equal to its temporal noise. It is basically the sensitivity of the IR imager; lesser the NETD, better is the detector.

Figure 17 (a) and (b) below depict various sub-technologies and processes involved in fabrication of cooled IRFPAs as well as the fabricated DDCA.

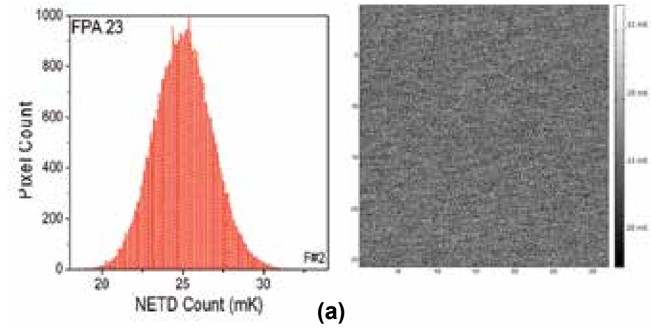


(a)

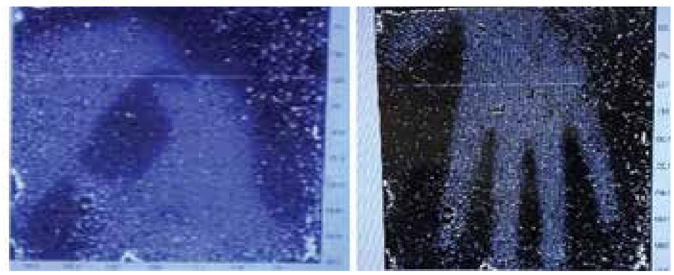
(b)

Fig 17 (a). Indigenously Developed Sub-technologies for Cooled IRFPA Technology (b) 640x512/384x288 FPA in DDCA

To get lesser NETD, the detector, ROIC, peripheral electronics, i.e., each individual constituents of the IR imager need to perform. It also depends on several other parameters, like, f-number of the optics, integration time and the scene contrast that again depends on the temperature of the scene. The estimated NETD of a best FPA fabricated at SSPL is shown below in Figure 18 (a) as 2D intensity map as well as in histogram form. The IR images were taken from a complete DDCA cooled with JT cooler. With this DDCA, IR images and videos of human target have been seen as shown in Figure 18 (b).



(a)



(b)

Fig 18 (a) The Measured NETD (in Histogram form as well as 2D Intensity map) of a Best FPA Fabricated at SSPL (b) MWIR Images of Human Target

Cooled IRFPA technology continues to expand at a rapid pace and further developments for military applications will be seen in the near future. The current R&D efforts worldwide are focused on developing High Operating Temperature (HOT) photo-detectors primarily for reducing SWaP and lower pitch arrays to reduce cost or improve the resolution. SSPL is also working on the development of HOT detectors and large format, small pitch MWIR arrays (1K×1K/10μm).

High Power Laser Diodes

High power laser diodes have numerous applications like range finders, dazzlers, proximity fuses, fencing, explosive initiation, etc. SSPL has developed various technologies for high power laser diodes involving single emitter laser diodes, arrays, stacks and Fiber Coupled Laser Diodes (FCLD) in different mode of operations and output powers for above applications. At present, SSPL is working towards establishment of manufacturing base in the country for current indigenous laser diode technologies. The scope of activity involves establishment of laser diode technology and prototypes development. The deliverables are prototypes of single emitter laser diodes and FCLDs.

Development of Laser Diode Module and C/F-mounted Laser Diode

Laser fencing is a technology for monitoring and sensing of unwanted or suspicious intrusion in the desired area. SSPL has developed modules for laser fencing systems. Laser diode module is the heart of fencing system. It includes a 1-2 W CW infrared wavelength laser diode on a c-mount package, laser collimation lens, a heat sink and a fan for air cooling of the module. Laser fencing modules for 100 m fencing range have been successfully tested and delivered to LASTEC (Figure 19). c-mounted laser diode units (Figure 20) were delivered to CEL, Sahibabad for their upcoming requirements as per the specifications listed in Table 2.

Fig 19. Laser Diode Module

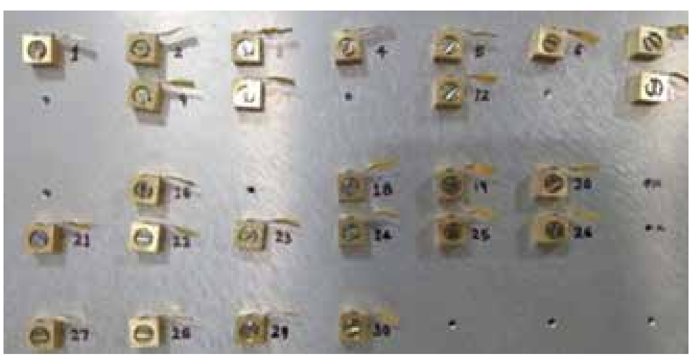


Fig 20. C-mounted Laser Diode

Table 2. Typical Specification of Laser Diode

Power output	1-2 watt
Wavelength	976 nm
Slope efficiency	~ 830 mW/A
Threshold current	~0.3Amp
Package	C-mount

SSPL is developing single stripe packaged laser diodes emitting up to 10W in CW mode. The chips have been jointly fabricated using SSPL's technology at GAETEC and SSPL and mounted on F-mount (10W, CW) packages as per the user requirements (Figure 21). Light-current characteristic of 10 W single stripe laser diode are shown in Figure 22. The 10 W CW single emitter fiber coupled laser diodes find application directly in initiation of explosives for detonation. C-mount laser diode are used in laser fencing application.

Fig 21. F-mount Laser Diodes

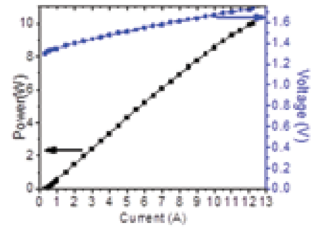


Fig 22. Light Current Characteristics of 10 W Laser Diode

Development of FCLD Module

The 10W CW single emitter laser diodes serves as the basic building blocks for development of higher power FCLD modules. These modules consist of multiple single emitters and after the beam combining of these single emitter the output is coupled to a multimode fiber. SSPL along with industrial partner is jointly developing 10W, 30W, 35W (Figure 23) and 70W CW FCLD modules emitting at 976nm.

The FCLD modules were tested at TBRL in initiation of explosives for detonation. The FCLDs also finds application for pumping of fiber lasers to enhance Power Levels. Further work is in progress to develop FCLD modules of higher power up to 250W and beyond.

Fig 23. Fibre Coupled Laser Diode FCLD-35

Blue/Green Laser Diode

Underwater communication is a key area for defence applications. Traditionally most underwater communication systems have been acoustic and have relatively low bandwidth. Sonar communication is used more often, but available modems and transducers are too large and very expensive.

High bandwidth, short range underwater optical communications have high potential to augment acoustic methods. Blue-Green region of the optical spectrum has the minimum attenuation in sea water. Communication between various underwater entities like submarine to Unmanned Underwater Vehicle (UUV) as well as underwater optical sensors can be realized using laser sources emitting in blue green region. A free space laser communication system operating in the blue-green portion of the spectrum has the potential to transmit at very high data rates under sea water.

The most promising and viable route for developing blue/green laser diode is to employ Gallium Nitride GaN-based material systems. InGaN/AlGaN/GaN based multiple quantum well laser structures are being used for developing such laser diodes. By choosing the indium content in $In_xGa_{1-x}N$ quantum wells in the active region, it is possible to realise laser diodes emitting in wavelength range 400 nm to 550 nm.

Major Challenges

GaN based laser structures are usually grown on c-plane. In addition to issues of spontaneous and piezoelectric polarization, there are various growth and fabrication challenges. Growth of green laser diode requires increase in the Indium (In) content in the InGaN Multi Quantum Well (MQW) layers. Growth of high-quality Indium rich InGaN/GaN QWs is still the major technical challenge due to several material related issues such as high lattice mismatch between InGaN and GaN, deterioration of the material due to low growth temperatures requirement, In-segregation and phase separation and p type doping. Further, p-ohmic contact fabrication is a major challenge due to requirement of high work function metal. Various metal schemes, viz. Ni-Au, Pd/Au etc. have been applied and further work is in progress to achieve low resistive p-contacts.

SSPL has recently started a research activity for the fabrication of InGaN/GaN based semiconductor lasers. Fabrication process includes stripe formation by mesa etching using Reactive Ion Etching (RIE) process, low resistance Ohmic contact formation on p and n side, thinning of epitaxial structure by grinding, lapping & polishing, cavity formation, facet coating, and packaging.

One of the major challenges in processing of GaN-based laser diode is in laser cavity facet formation. Typically, laser cavity facets are made by cleaving the semiconductor material. For c-plane green lasers, m-plane cleaved-facets may be formed by cleaving, as the m-plane is favourable for cleavage propagation. However, for semi-polar orientations the choice of stripe direction is limited and facet formation by cleaving is very difficult.

The optical gain in the InGaN QWs is relatively low. The total optical losses have to be minimized to reach lasing conditions at moderate current density. Both facets are required to be coated with high reflection films to reduce the optical losses and so the threshold current, however the output power is reduced. In order to maintain a high Wall Plug Efficiency (WPE) and obtain high output power, the reflectivity of the front facet has to be reduced to an optimised value.

Fig 24. Blue Green Laser Diode

At SSPL research is being pursued to address all the processing related issues. Recently, GaN-based single emitter laser diode has been fabricated and lasing action has been realised (Fig 24) in CW and pulse mode. Figure 25 & 26 show the spectrum and L-I characteristics of fabricated laser diodes. Laser emission was observed at 410 nm wavelength

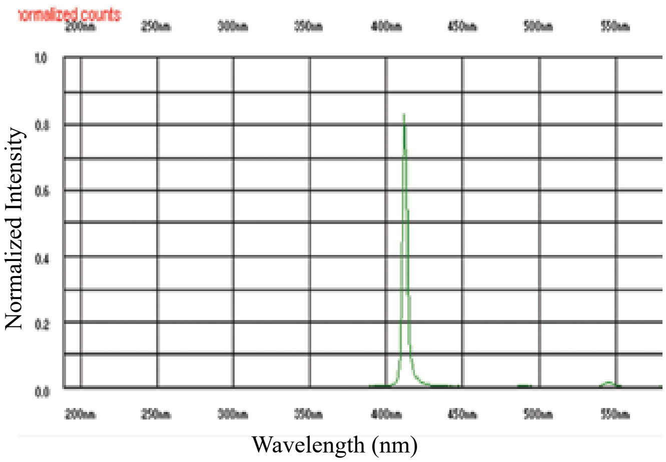


Fig 25. Spectrum of Laser Diode Device

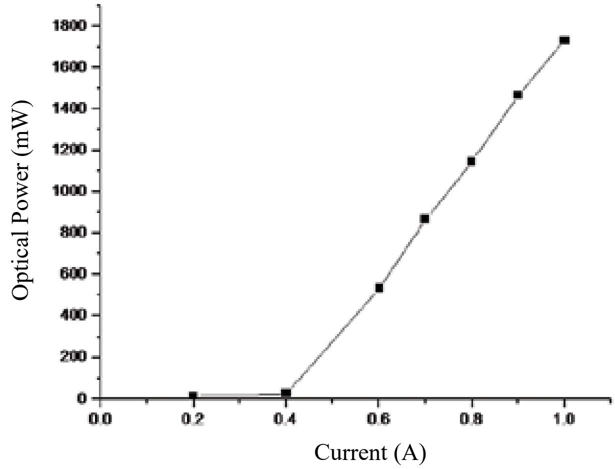


Fig 26. L-I Characteristic of Laser Diode

In more than 100mW power in CW and >1W peak power pulsed mode has been achieved. Further work is in progress for development of GaN-based blue green laser diodes.

SENSOR TECHNOLOGY

To make our Armed Forces better equipped to deal with any kind of battlefield situations where outbreak of any chemical or biological agents or destructive radiations, there is need to develop and fabricate sensors that push the limits of sensitivity and selectivity. Besides Chemical Biological Radiation and Nuclear (CBRN) sensors other physical sensors such as underwater acoustic sensors are need of the hour. Next generation sensors are expected to be more sensitive and reliable, in addition to being small in size and low power consumption. Future systems are expected to have much more situational awareness. This necessitates improving the performance of existing devices and exploration of new application areas, which were previously not thought of.

Chemical Warfare Agent Detector-e-Nasika

SSPL has developed a ruggedized, handheld electronic nose vapour detector for Chemical Warfare Agents (CWA) known as e-Nasika, under NBC program. The e-Nasika system is a SAW-GC (gas chromatography) based system which is capable of detecting lethal CWA like Sarin, Soman, Tabun, VX, Lewisite (G Agents), Sulphur Mustard (H Agent), Phosgene (choking agent), Hydrogen Cyanide (blood agent) and other agents, with concentrations in low ppb and in less than a minute time. The developed system has been tested and certified by TNO, Netherlands, an independent testing and certification agency in the field of NBC. The system has met the JSQR performance criterion laid down by the Services. (Figure 27).

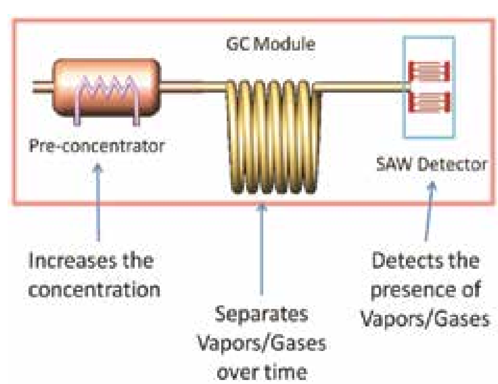


Fig 27. e-Nasika

Development of CNT-based Hand Held Chemical Detector-n-Nasika

Most Explosive Devices (IEDs) are based on nitro-aromatic compounds and releases NOx on explosion. Moreover common IEDs used in insurgency are made of ammonium nitrate, which releases NO_2 and NH_3. Thus sensors with high sensitivity are required to detect these gases.

SSPL is developing CNTs-based Gas Sensors (CBS) for ppt level detection of NH_3 and NO_2. CBS are next generation sensors having ultra-high sensitivity, room temperature operation, tunable selectivity and ease of miniaturisation.

Arrays of CNT sensors have been fabricated over a 2 inch porous alumina substrate, with around 40 to 50 devices per substrate (Fig 28 a) Each device with size of 4 mm x 4 mm, is actually an array consisting of 4-8 elements (Fig 28 b) . Each element of the array has been individually functionalised so as to obtain selectivity for the target analyte gases. A gas cell has been designed for sensor housing, which has gas inlet & outlet and is equipped with a UVLED and heater for gas desorption, and also a pressure, humidity and temperature sensor to control the gas sensor environment conditions (Fig 28 c).

Fig 28 (a) **Image of 2 inch Alumina Membrane with 50 Device Arrays**

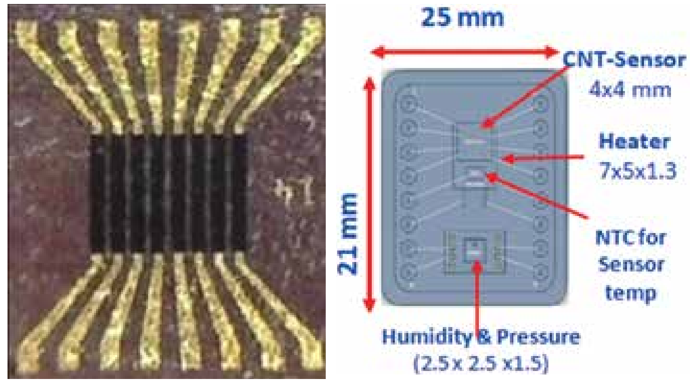
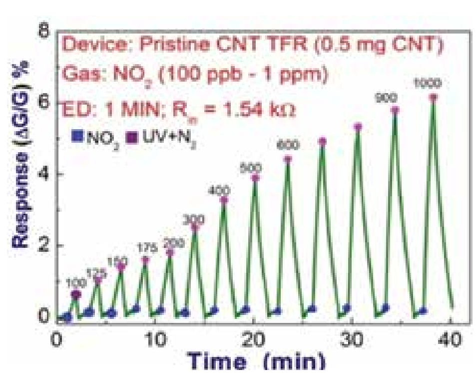
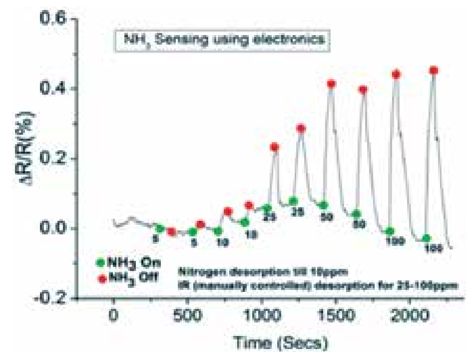


Fig 28 (b) Fig 28 (c)

Fig 28 (b) Image of a 8 Finger Device Array (c) Schematic of the Gas Cell

Using a rduino-based microcontroller complete automation of the entire sensing application, comprising of sequential gas absorption and desorption, automated switching of the peripherals like micropumps and valves, and control of MFC using a ADC/DAQ system has been developed for in-lab training and calibration of the sensor. The operation of peripheral and electronic components (as mentioned above) are controlled via digital switching of driver ICS from microcontroller digital pins. Front end in the system, comprised of a 24 bit ADCs for automatic data acquisition with accuracy better than 5 digits. Ratiometric configuration is implemented for this purpose. The value of the change in resistance due to gas absorption/ desorption was acquired from microcontroller to computer. This system was regularly used for automated sensing of gases like NO_2 (Fig 29 a) and NH_3 (Fig 29 b) at different concentrations sequentially Further this system was also tested for detection of explosive compounds like Ammonium nitrate which is commonly used in explosives (Fig 29 c)





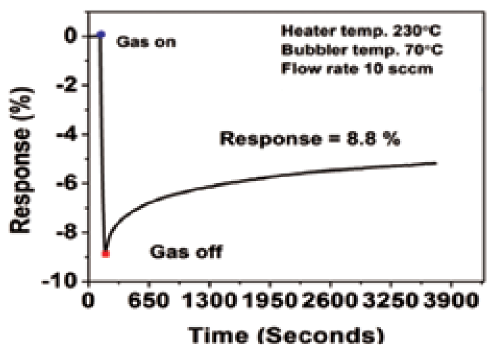


Fig 29. Sequential Sensing of Gases over Different Concentrations (a) for NO_2 and (b) for NH_3 (c) Response of Sensor for Sensing of Ammonium Nitrate

A complete hand held prototype for detection of NO_2 and NH_3 has been developed for on-field detection. This prototype n-Nasika (Fig 30) has been demonstrated during various exhibitions as well as DefExpo and Aero India.

Fig 30. n-Nasika-Automated Handheld CNT-based Gas Sensor

ACADA

SSPL has also developed Automatic Chemical Agent Monitor and Alarm (ACADA) system, modified version of present e-Nasika system. The system has a remote display unit which can be connected through cable and can be operated remotely. The remote display incorporates all the system display features and can remain at 1 km distance from main ACADA system. The sensing technology and specifications in both e-Nasika and ACADA are same. (Figure 31).

Fig 31. ACADA

Technology Breakthrough

The technology breakthrough was achieved with the realisation of fast gas chromatography operation, by reducing the conventional GC response time from about 20 minute to 30 seconds. Both products use the miniaturized GC module with SAW device as detector.

Major technology achievements and their details are:

- Compound Detection: All compounds are detected as a whole and not by its constituent elements.
- Simultaneous Detection: All the targeted compounds simultaneously in one go. No mode change needed. Single unit for G, H, B, C, and TIC/TIMs.
- Insensitivity to Physical Changes: SAW e-Nasika has temperature, pressure/flow controlled internally. External variations do not affect the response. Humidity is detected as a separate compound.
- Saturation Proof: Detects from ppb to very high concentrations and quickly returns to normal.
- Wide Compound Library: Large library compounds are possible.
- Low False Alarms: Use of GC and compound detection leads to better selectivity and low false alarms.
- Indigenous technology: >70% indigenous.

Potential Applications

The technology has potential application in development of explosive detection. This will act as force multiplier for home land security agencies like paramilitary forces, NDRF, NSG, SPG, etc.

Compounds Detected	Nerve (Tabun, Sarin, Soman, Cyclosarin, VX), Blister (Sulphur Mustard, Lewisite), Blood (Hdrogen Cyanide), Choking (Phosgene), TICs/TIMs
Identification	Automatic
Detection Time	12 to 55s
Sensitivity	Sarin: 0.05 mg/m³, Sulphur Mustard: 0.5 mg/m³, HCN: 20 mg/m³, Phosgene: 20 mg/m³
Alarm	Audio & Visual
Size	30 x 10.5 x 12 cm³
Weight	3 kg with batteries
Operation	> 8 Hours Continuous
Ruggedisation	JSS55555 & MIL STD 461E

Acoustic Sensor

SSPL in collaboration with NMRL, designed, developed and standardized completely indigenous technology for fabrication of miniaturised, highly sensitive, omni-directional FET input-Piezo-based acoustic sensor for naval and marine systems. Technology for these sensors has been developed using hybrid interface electronics in close proximity of 1-3 Peizocomposite/PVDF/PZT sensing element, both encapsulated in acoustically transparent Polyurethane (PU)/Epoxy. It is capable of providing miniaturized, low cost, light weight, high sensitivity acoustic sensor with desirable flat frequency and omni directional response for different applications. These acoustic sensors were extensively evaluated for receiving voltage sensitivity and directivity at acoustic test facility-NSTL Vizag, NIOT, Chennai, and NPOL; and also for temperature tolerances at MATS facility NPOL. The single-element miniaturised acoustic sensors & arrays meeting specifications were delivered to user, for Naval & Marine Systems for testing w.r.t. to projected QRs and system application.

Single Element Mobile Decoy Acoustic Sensor

The mobile decoy acoustic sensor (Fig 32) is capable of detecting an incoming torpedo. The mobile decoy helps in protecting the naval platform by exhausting the energy of the torpedo by running in long and zigzag course to prevent the enemy torpedo from homing the Naval platform with its advance sophisticated counter-measure algorithm. Acoustic sensor for mobile decoy having Receiving Voltage Sensitivity (Rvs) -170 dB re 1V/µPa (±2dB) in the frequency band (15 KHz to 85 KHz) as shown in Figure 32 (a) and 100 nos. were delivered to NSTL.

Thin Line Towed (TLTA) Array Acoustic Sensor for AUV Application

An Autonomous Underwater Vehicle (AUV) performs the function of Intelligence, Surveillance, and Re-connaissance (ISR).Technology developed for miniaturised TLTA (Figure 32 b) acoustic sensor using fully differential hybrid interface electronics in close proximity of PZT micro tube sensing element, both encapsulated in acoustically transparent Polyurethane (PU) for TLTA & embedded application in rubber acoustic tiles, fitted on to AUV.

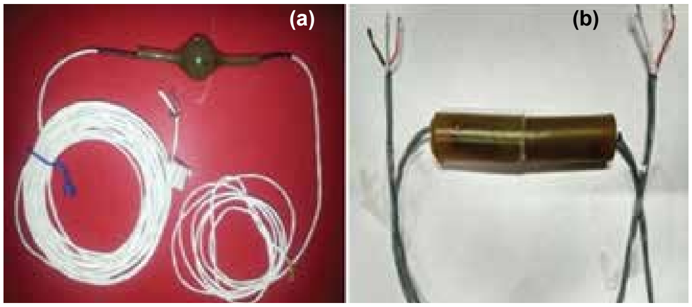


Fig 32. (a) Single Element Mobile Decoy
(b) TLTA Acoustic Sensor

Acoustic Sensors for Underwater Mines

Acoustic sensor for detection Mines (Fig 33) application having Receiving Voltage Sensitivity (Rvs) -170 dB re 1V/µPa (±2dB) in the frequency band (2-20KHz) & omni directional (Horizontal Plane) response were developed and delivered to NSTL.

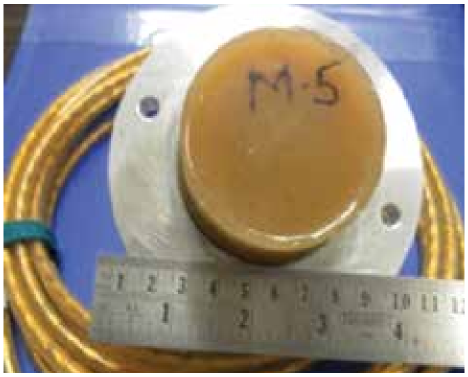


Fig 33. Mines

Acoustic Sensor for Buried Object Scanning Sonar

Buried Object Scanning Sonar (BOSS) is used for minerals during imaging at sea bed. The same may be used for mine hunting. SSPL in collaboration with NIOT has developed acoustic sensor for BOSS in the frequency range 2-30 KHz having sensitivity RVS=-165 dB re 1V/uPa, with flat & omnidirectional response as shown in Figure 34.

Fig 34. BOSS Acoustic Sensor

Sensor Array for ambient noise measurement of sea. 12-element ambient noise measurement acoustic sensor array (Fig 35) encapsulated in PU (100 Hz-30 KHz) having sensitivity RVS=-170 dB re 1V/uPa, with flat & omni-directional response has been designed, developed, and delivered.

Fig 35. 12-element Acoustic Sensor Array

Piezo-based Indigenous AE Sensors and DAQ System for Avalanche Prediction Applications

SSPL in collaboration with NMRL and DGRE has developed indigenous technology for fabrication of rugged, high sensitivity (better than -30dB @1V/µbar), wide bandwidth (20-80 kHz), unidirectional AE sensor and AE Acquisition and Analysis (DAQ) system for snow avalanche prediction application (Fig 36 a). Indigenous AE sensor consists of 1-3 piezocomposite sensing element and having 26 dB integral pre-amplifier gain. Indigenous DAQ system is having 32/16-AE channels capable of 1 MSPS maximum sampling rate, multiple AE parameter extraction from AE signal (amplitude, counts, AE energy, peak, and average frequency, pulse duration, etc.) and operating temperature range of -20 °C to 55 °C.

Captured AE waveform's shown in (Fig 36 b). The indigenous AE sensor system has potential applications in the field of Structural Health Monitoring (SHM) of various steel and concrete constructions and structures, leakage detection, corrosion detection, aircrafts structural integrity monitoring, and pressure vessel SHM, etc.

(b)

Fig 36. (a) Indigenous AE Sensor and AE DAQ System, (b) Captured AE Waveform with Extracted AE Parameters

AE sensors (320 Nos.) and DAQ System (08 Nos.) were successfully delivered and deployed at different avalanche prone sites on Manali-Leh axis (Dhundi and Patsio, HP) and J&K (Banihal Top). The AE sensor system is working in 24x7 mode on these avalanche prone sites and collecting AE data. The data will be analysed by DGRE for developing a snow avalanche prediction model. SSPL successfully transferred technology to M/s Canopus Instruments, Thane for AE sensors and M/s Digilogic Systems Pvt. Ltd., Hyderabad for AE Acquisition and Analysis (DAQ) System.

Future Plans for Sensors

Landslide Early Warning System-based on AE Technology

SSPL has gained experience in design and development of indigenous AE sensors and DAQ system from its past project. The experience will be utilised for developing AE sensor system for monitoring landslide events and further analysing the trends of AE behaviour leading to the real-time landslide event. Machine learning methods and artificial intelligence for the post-analysis of collected AE data will be used to develop an algorithm for Landslide Early Warning System (LEWS).

Design and Development of Indigenous Acoustic Vector Sensor

Acoustic Vector Sensor (AVS) can be used for various applications like direction of arrival estimation, infrasonic sensing, etc. SSPL is working towards the development of AVS

Blast Sensors

SSPL is working on development of indigenous pressure sensors based on piezoelectric element. Application of blast sensors will be for detection of various shock waves, blast or explosive testing.

Infrasonic Sensors

SSPL is involved in the design and manufacturing of infrasonic sensors. Typical application of infrasonic sensors will be to detect and capture infrasonic waves for various events like snow avalanche, air turbulence detection, and earthquake activities, etc.

SAW-based e-Nasika

The technological achievements of SAW-based e-Nasika system will be utilised for developing a 24x7 operated CWA detector for application in places of strategic and public importance and for vehicle mount CWA monitoring.

CNT-based Gas Sensor

The way forward after CNT-sensor training and using artificial intelligence software the sensor module will be used for screening variety of explosives, CWAs and other toxic gases like an e-nose.

MEMS-based Acoustic Vector Sensor

Indigenously developed AVS will be utilised for estimating direction of arrival of incoming acoustic signal. Typical application: Gunshot localisation

THz Technology

SSPL has plans to develop THz detector using graphene because of its high carrier mobility, zero bandgap and strong interband absorbance in all THz frequency which provides wideband THz detection. THz imaging due to non-ionising radiations is very pertinent for homeland security. THz spectroscopy provides unique fingerprints of explosives, CWAs and other materials. (Fig 37)

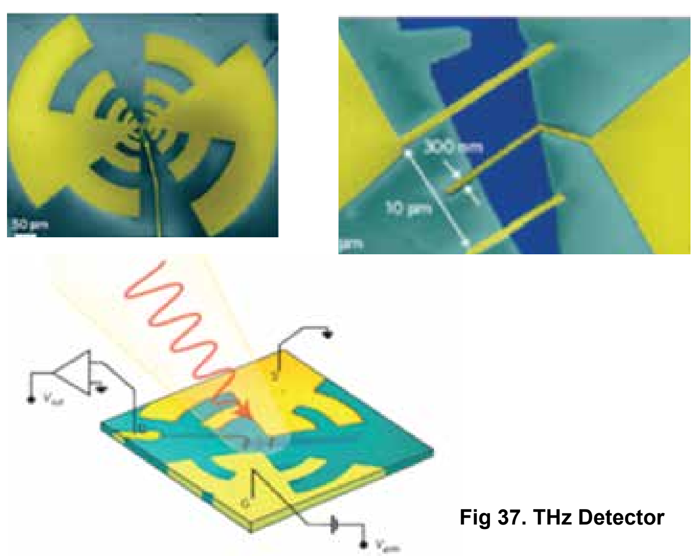


Fig 37. THz Detector

Study of Propagation of Blue/ Green Laser as a function of sea water

Futuristic emerging requirement of underwater mines, underwater communication, AUV/UUV submarine communication and turbulence detection systems based on blue/green laser technology demands detailed experimental data/real time data for propagation of blue/green laser in sea environment.

In view of above SSPL has plan for detailed experimental study of propagation of blue /green laser parameter as a function of water parameter, e.g. salinity, conductivity, turbidity, organic matter, temperature, pressure, etc. This study will help in optimising blue/green laser-based system parameters.

COOLING TECHNOLOGIES

Thermoelectric Cooler Technology

Thermoelectric Coolers are solid state cooling devices based on the Peltier Effect which can provide localised cooling or heating on the application of a DC voltage. These devices find widespread use in defence systems and sub-systems for cooling and temperature stabilization of active devices such as laser diodes, infrared FPAs and other sensors.

SSPL has developed the technology for design and fabrication of single stage thermoelectric cooler modules based on Bi_2Te_3 alloys. The complete technology development consists of thermoelectric material optimization, device design and performance simulation, and standardization of the process sequence for fabrication of cooler modules reliably and reproducibly. Polycrystalline ingots of p-type and n-type Bismuth Telluride alloys with figure of merit $> 2.5 \times 10^{-3}$ /K were grown using vertical directional freezing. Modules have been designed for different in-house applications based on user requirements. The complete process sequence, which consists of several sub-technologies such as development of metalized alumina substrates, development of miniature thermo-elements, design of demountable assembly jigs, optimisation of soldering procedures for module assembly and testing of module characteristics has been optimised.

Single stage TE cooler modules (Fig 38) have been developed for applications such as cooling/ temperature stabilization of laser diode, Ti-based micro-bolometer arrays, InGaAs-based SWIR detectors, cooled garments, etc. Cooler modules with sizes ranging from 10X10 to 50X50 sq mm and capable of pumping heat in the range of 1W to 30W have been designed and fabricated as per the requirement. The operating currents of these modules are in the range of 250mA to 10A. Maximum temperature differential of upto 64K can be achieved across the device. Scale up of device numbers has been achieved through interface with an industry partner.

Multi-stage TE cooler modules (Fig 39) have been developed to obtain higher temperature differentials (> 64K) .

This development makes it possible to custom design the optimum modules for any application based on the user requirements and fabricate them indigenously.

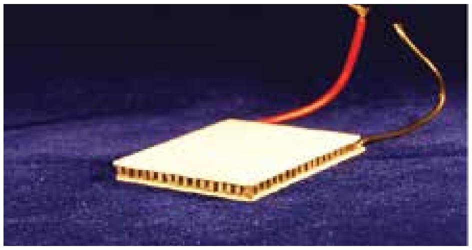


Fig 38. Single Stage Cooler

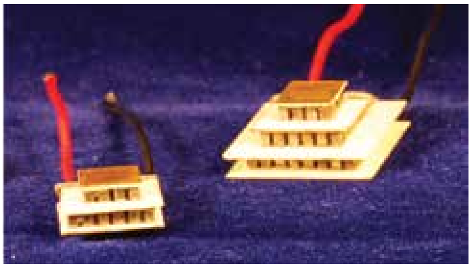


Fig 39. Multistage Cooler

Development of Bi_2Te_3 Alloy-based Nanocomposites

After successful development of technology for single-stage and multi-stage TE coolers based on bulk Bi2Te3, work on the development of Bi_2Te_3based nano-composites has been initiated. To enhance the figure of merit (ZT) of thermoelectric materials at low temperatures, recent work focused extensively on nano-composites that consists of thermoelectric matrix and dispersed nano-sized particles. SSPL has set-up a facility for preparation and thermoelectric characterisation of thermoelectric nano-composites. This development work can be broadly divided into:

Preparation and Thermoelectric Characterisation of Nano-Composites

- Preparation of nano-sized powders of alloys matrix by Ball milling with or without nano inclusions
- Compaction of nanopowders into cylindrical pellets followed by annealing under optimised conditions
- Characterisation of thermoelectric properties at temperature ranging from 150-350K

Fabrication and Testing of Prototype TE Cooler Module

- Metallisation on nano-composite samples for providing low resistance contacts consisting of optimisation of processes for electropolishing, electroless Ni deposition followed by Ni electroplating
- Preparation of thermeo-elements, unit couple fabrication and their testing

Based on the concept of nanostructured materials, novel nano-composites using alloys of Bismuth Telluride as the matrix element, have been prepared and characterized for their thermoelectric properties. Nano-sized inclusions such as Si, Cu, SiC, CNTs and Graphene have been dispersed within the matrix to study their effect on the thermoelectric behavior of the nano-composites. The size, concentration of the nanoinclusions as well as the annealing conditions were varied after which the thermoelectric parameters and the figure of merit at various temperatures was evaluated and compared with that of the bulk alloys.

For preparing the nano-composites, optimised compositions of p type $Bi_{0.5}Sb_{1.5}Te_3$ and n type $Bi_2Se_{0.7}Te_{2.3}$ were synthesized, and used as feed for the planetary ball mill (Restch PM-100) to be ground down in nano-sized powders. Various nano-particles, viz. Cu, Si, CNT and Graphene in different concentrations are added to nano-structured matrix material to prepare p and n type nano-composites.

The ball milled powder is compacted in the form of cylindrical pellets of 13 mm and 20 mm diameter with the desired thickness using an automated cold press. The compacting process was optimized to achieve high density and smooth finish in both p and n type nano-composites pellets. These pellets are sealed and annealed at optimized temperatures and durations to attain the desired thermoelectric properties. The annealed nanocomposite samples were further characterised for their structural and thermoelectric properties using the ZEM-3L and XFA system.

Study of nano-composites showed that as expected, nano-structuring brings about a significant reduction in the thermal conductivity of Bismuth Telluride alloys. However, simple nano-structured samples show much higher resistivity, therefore the overall Z decreased.

Addition of minimal amount of nano-inclusions (0.1 to 0.3 wt%) brought about significant change in the resistivity & Seebeck coefficient in these nanocomposites. The actual increase/decrease, depends on the nanoinclusions species, their size, concentration and the annealing conditions. The effect of 10-50 nm sized Cu, Si, SiC, MWCNT, Graphene as nano-inclusions with varying concentrations, on the thermoelectric properties in the 150-300K temperature range have been studied systematically. Based on these studies, p and n type nano-composites with enhanced Z at low temperatures have been identified. Enhanced thermoelectric figure of merit (ZT) at low temperature 150-300 K obtained in p type nano-composites with CNTs (0.05 and 0.1 wt%) and Graphene (0.4 wt%) as nano-inclusions. For n-type nano-composites, ZT enhancement at lower temperatures was seen with CNT (2wt %) and Si (0.2 wt %) as nano-inclusions (Fig 40). Work for further enhancement in ZT values for n-type nano-composites is to be carried out.

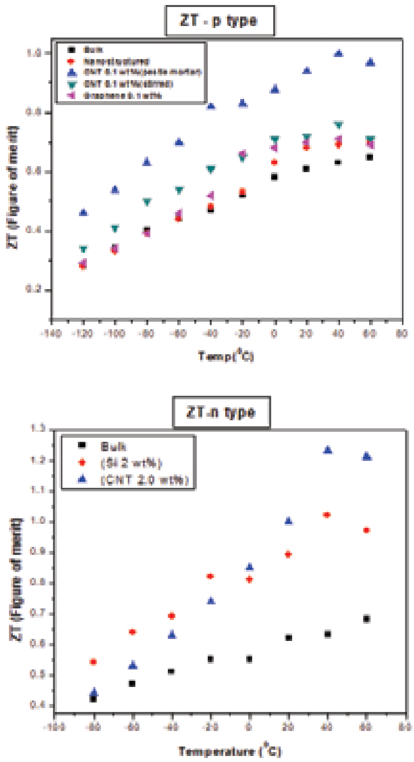


Fig 40. Nano-inclusions

Further, for fabrication of thermocouples, work on obtaining Ni contacts with good adhesion on these nano-composites has been done for the first time. This is significant because so far, no research group worldwide has reported success in this area. Some more work is required in the area of obtaining low-resistance metal contacts to the nano-composites so that further improvement in the performance of TE devices can be achieved.

Using the nano-composites with enhanced Z, prototype TE coolers have been fabricated successfully and tested. A maximum temperature differential (ΔTmax)≃32-34 °C has been obtained in these devices. These are among the first cooler module performance results reported by any group worldwide using nano-composites. Work on further optimization of the Ni interface as well as exploration of new metal schemes for achieving the same is in progress for realising the effect of the improved ZT in these devices.

Stirling Cryocooler

Stirling Cryocooler is used for cooling of Infrared Focal Plane Arrays (IRFPAs) being developed at SSPL and is also suitable for commercially available detector arrays. These IRFPAs have to be maintained at cryogenic temperatures of the order of 80 K for their normal operation. Cryogenic temperatures are produced by mechanical closed cycle Stirling Cryocoolers. These Cryocoolers work on Stirling Cycle and are characterized by high efficiency, fast cool down time, smaller size, lightweight and high reliability.

SSPL has developed the technology for rotary crank driven cryocooler based on Integrated Detector Dewar Cooler Assembly (IDDCA) configuration. The prototype is suitable for linear array as well as IRFPA formats. Technological complexity and requirement of long duration fail-safe operation of the cryocooler demands robust design, fabrication and assembly with close tolerances, and perfection of an array of sub-technologies. The prototypes developed have been subjected to several hundred hours of laboratory testing as per standard test protocols successfully. A screen-shot of a typical performance test is shown in the Figure 41. The same has been integrated and tested with commercially available IDDCA modules at BEL-Machilipatnam (Fig 41) and clear thermal images were obtained. These prototypes suits to modern day thermal imagers in various sensor array formats and are at par with the state of the art. The technology (ToT) has been transferred to BEL- Machilipatnam for indigenous production.

Fig 41. Stirling Cryocooler Prototype

Specifications:

- Cooling Capacity : 0.5 W @ 80 K
- Cold Finger Size : 8 mm max
- Cool-Down Time : < 6 minutes
- Type of Drive : Brushless DC motor
- Feedback Control : Yes
- Max. Input Power : 20 W
- Steady State Input : 10W @ 80K
- Weight : < 450 gm

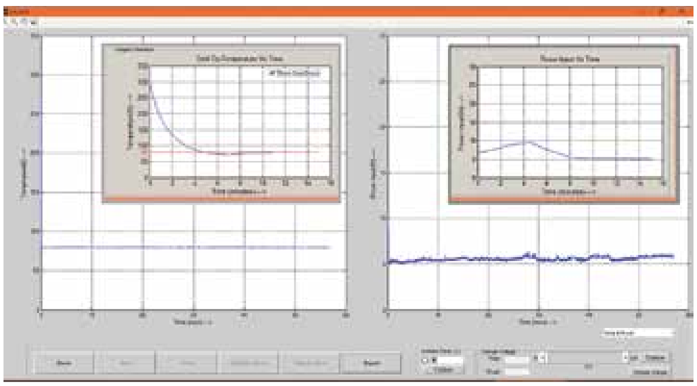


Fig 42. Test Results of a Typical Performance Run (DAQ Screen-shot)

Fig 43. HHTI Fitted with Cryocooler Prototype

Self-regulating JT Cooler for Cooled-IR Detectors

A Dewar is a vacuum encapsulation, used for packaging cooled-IR Detectors, which need to be operated at cryogenic temperatures of about 80K to 90K. The dewar basically insulates the detector from atmospheric heat so that it can be easily cooled to the desired cryogenic temperature and thereafter can be maintained at that temperature, so long as the detector is operational. Normally, a Joule Thomson (JT) cooler is used for this purpose, as it is quite compact, offers minimum weight (10-15 grams), have no moving parts and offers a very quick cool-down time of the order of about 7 to 20 seconds.

A JT cryo-cooler is fundamentally a counter flow heat exchanger and a nozzle which produces refrigeration based on the joule Thomson principle of isenthalpic expansion of a refrigerant (high purity nitrogen or argon) from a high pressure and temperature to a lower pressure and temperature. Cryo-coolers are often rated by their available refrigeration capacity measured in watts, at a particular temperature, at which the refrigeration is available, for example 1W at 80K. A JT cooler works on an open cycle. Another important parameter is the power input or work required to achieve refrigeration. The Coefficient of performance of a refrigerator is defined as the ratio :

COP = Refrigeration capacity/power input = Heat abstracted/work done

The ideal Coefficient of performance is the Carnot value: COP (Carnot) = $T_L / (T_H - T_L)$

Where, T_L is the lowest cycle temperature (refrigeration temperature) and T_H is the maximum cycle temperature, generally the ambient temperature.

The ratio of the actual COP to the Carnot COP is called the cooler efficiency. In fact, it is the useful measure of the way, an actual machine measures up to the thermodynamic ideal machine. Thus, Cooler efficiency = actual COP/Carnot COP

With Nitrogen as the working fluid producing liquid nitrogen at 78K from the inlet gas at 300K, it is observed that an input power of 33.5W is required to produce a refrigeration output of 1W. Thus, it gives the actual COP of the JT cooler as 1/33.5 = 0.03, whereas for the ideal Carnot cycle the COP will be = $T_L / (T_H - T_L) = 78/(300-78) = 78/222 = 0.35$.

Thus, efficiency of a JT cooler = (Actual COP/ Carnot COP) = 0.03/0.35 = 8.57 %

Developed JT Cooler

So far a Constant flow JT cooler, as shown in Figure 44, has been developed at SSPL, using all indigenous parts, except fin-tube. On cooling test at Room temperature this cooler has produced the liquid Nitrogen within the desired cool-down time of about 30 secs with a supplied Nitrogen gas pressure of 3000psi (208 bar).

Fig 44. A Constant Flow JT Cooler

However, a constant flow JT Cooler can not regulate the mass flow of cryogen on achieving the desired cold-temperature, thus resulting in a huge consumption of high purity (6N pure) gases, which are available in a limited quantity on a missile carrier. Thus the use of a self-regulating JT cooler in the actual condition is a must. (Fig 45).

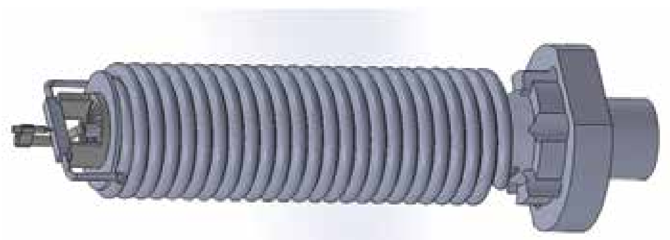


Fig 45. A Self-regulating JT Cooler

Advantage of using a Self-regulating JT Cooler: In a self-regulating JT cooler, as soon as the desired cold temperature of 80/90 K is achieved, a built in self-regulation mechanism in the JT cooler reduces the mass flow of the cryogen to just 5% to 10% of its initial value, thus economizing a substantial reduction of the gases supplied resulting in much longer operation of the coolers .

The work to develop a self regulating JT cooler is in progress at SSPL. All efforts are being made to realise the self regulation mechanism of this JT cooler. The exploded view of the self-regulation mechanism of the JT cooler is shown in Figure 46 and a cut section of the complete self-regulating JT cooler is shown in Figure 47.

Fig. 46 An Exploded view of the Self-Regulation Mechanism of JT Cooler

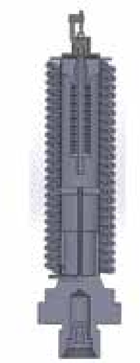


Fig. 47 Cut Section of SR-JTC

So far the metallic bellows, which is the heart of this mechanism, have been realized. A mini flexure spring, to keep the needle movement of the needle-valve perfectly straight over the JT orifice, has also been designed and subsequently fabricated .

The other miniature parts have also been designed and fabricated. Thus having realised all the necessary hardware, attempts have been made to integrate few assemblies of this regulation mechanism but the perfection in its working under a high gas pressure of about 27 bar is still in progress.

Development of Self-Regulating JT cooler

SSPL has experience of developing a primitive miniature JT cryo-cooler and has the appreciation of technological complexities involved in the development of advanced versions. To evolve a production setup for these coolers in the country, the laboratory has explored the possibility of involvement of some private industries having experience in fine machining capabilities/experience and has primarily ascertained that the relevant capabilities/knowledge is available in the country.

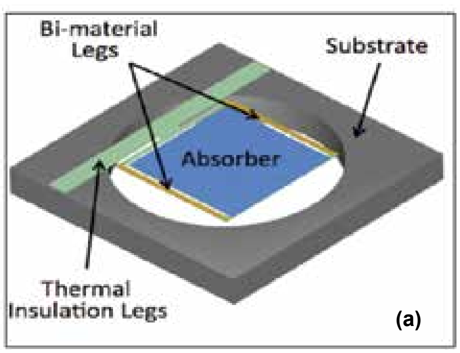
So development of Self-regulating JT cooler is going on under Technology Development Fund.

EMERGING TECHNOLOGIES

MEMS-based THz Detector

Terahertz (THz) waves, refer to electromagnetic radiation in the frequency range from 0.1 to 10 THz. (1 THz = 10^{12} Hz), which correspond to the wavelengths between 3 mm and 100 µm. Explosives, like, HMX, RDX, PETN, etc. have unique spectroscopy features in THz frequency range. Hence THz is being widely researched for their applications in solving security and anti-terrorism problems. THz is non ionizing yet can penetrate some distance through body tissue, so it is of interest as a replacement for medical X-rays. Furthermore, the most common non-polar substances are transparent to it and have spectral fingerprints in the THz frequency range creating interest for research in scientific and applied fields including non-destructive testing, medicine etc. THz communication is another important area of research as it offers higher bandwidth and resolution as compared to microwaves. The technology in this spectral region is still in its infancy and generally referred to as THz Gap.

The MEMS-based THz detector comprises of two main regions having (a) bi-material elements (micro-cantilevers or legs consisting of materials with different coefficients of thermal expansion) and (b) meta-material absorber, as shown in Figure 48. Meta-material structure has a stack of three layers, viz., metal, dielectric and metal fabricated with suitable dimensions and shape to maximize absorption in a fixed wavelength band. The absorbed THz radiation is converted to heat on the pixel. This causes an increase in the temperature of the released pixel and induces mechanical deflection in the bi-material micro-cantilevers due to different coefficients of thermal expansion of the two materials.



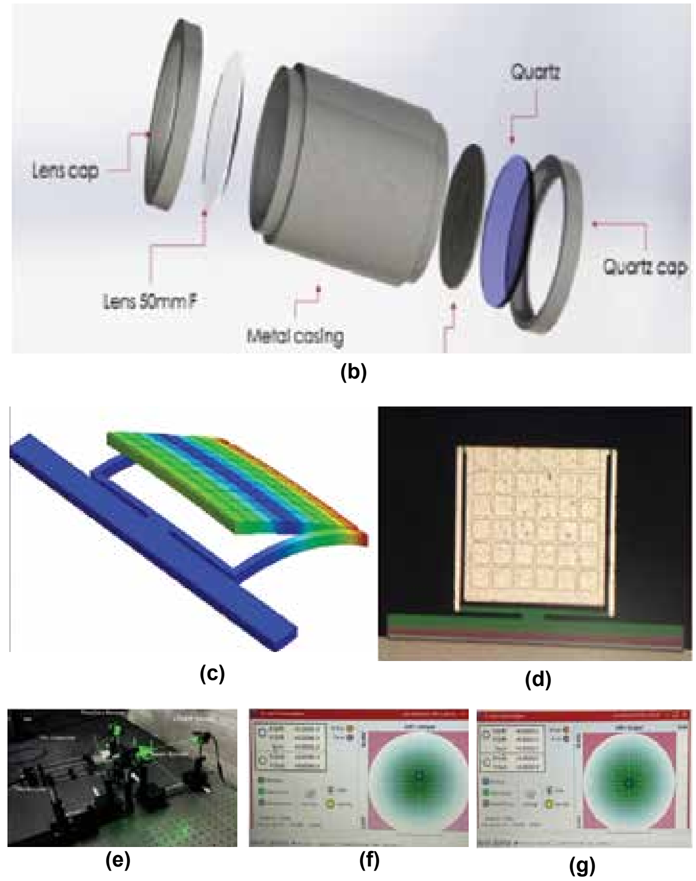


Fig 48. (a) & (b) 3D View of the THz Bi-material Sensor with Meta-material Absorber on a Si Substrate. (c & d) Fabricated THz Detector and its Package (e) Experimental set up to Demonstrate THz Detection (f&g) Position of Laser Beam before and after THz Absorption by the Detector.

The designed MEMS THz detector is successfully fabricated at STARC and its functionality has been demonstrated using optical readout. SSPL is also working on design of MEMS based THz detector array as well as THz Bolometer technology.

Photoconductive Antenna (PCA)-based THz Technology

The ability of THz radiation to interact differently with benign and threat materials as a function of THz frequency makes it important for security screening based on spectroscopy. Terahertz radiation is readily transmitted through most non-metallic and non-polar mediums, thus enabling THz systems to 'see through' concealing barriers such as packaging, corrugated cardboard, clothing, shoes, bookbags, etc in order to probe the potentially dangerous materials contained there. Many materials of interest for security applications including explosives, chemical and biological agents have characteristic THz spectra that can be used to fingerprint and thereby identify these concealed materials.

Among the different types of THz sources, Photo Conductive Antennas (PCAs) have unique advantage for the generation and detection of Terahertz for the spectroscopy and imaging application; as they are compact, reliable and does not require a vacuum or cryogenic cooling. PCA based source provides THz emission with μWatt power and broad bandwidth (~ 6THz) at room temperature. PCAs operate on the principle of photoconductivity, which allows for compact integration with a fiber optic laser and it can be used for making a robust THz spectroscopy system. The PCA consists of a DC biased metal dipole antenna patterned on a photoconductive substrate with ultrashort carrier lifetime (<1ps). The femtosecond optical pulse is incident on the antenna gap, and generates photocarriers inside the photoconductor as it is absorbed. The generated photocarriers are accelerated in the DC bias field, producing a transient photocurrent, which drives the dipole antenna and ultimately emits as a THz frequency pulse. THz generation in PCA by fs Laser and the typical PCA device mounted on HRFZ Si lens is shown in Figure 49.

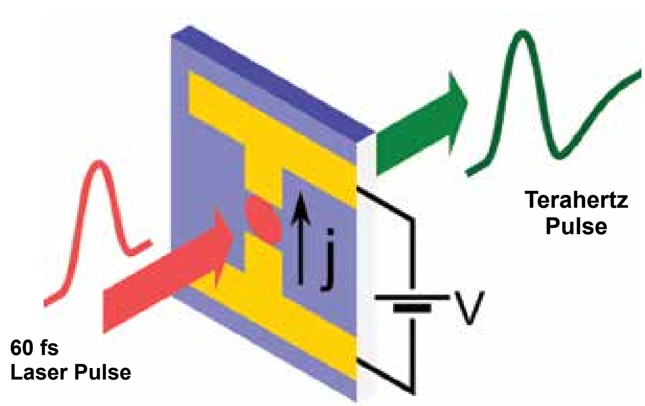


Fig 49. (a) THz Generation in PCA by fs Laser

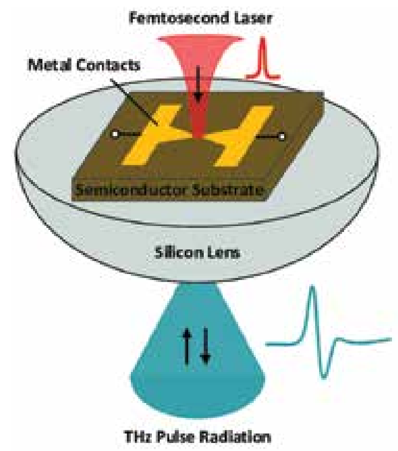


Fig 49. (b) PCA Device Mounted on HRFZ Lens

The laboratory is on targeting development of indigenous Photo Conductive Antenna (PCA) based THz source and detectors along with development of required (low-temp) LT-GaAs and LT-InGaAs material. The technology for material and device development is very challenging and SSPL ambitiously targeting delivery of~60 μW THz source. The laboratory is also planning to develop an indigenous THz time domain system (THz-TDS) and it will be customised for demonstrating completely indigenous THz imaging and THz spectroscopy system for short range (~1-feet) applications.

Graphene THz Technology

Graphene is a zero band gap material, the conduction band and valence band touch each other at Dirac point and there is linear energy- momentum dispersion which in turn results in various interesting optoelectronic properties. In the THz region, graphene has strong intraband absorption properties and it is a promising material for detection, generation and modulation of THz radiation.

SSPL developed the technology for the fabrication of graphene based THz devices. This technology development involves graphene growth, simulation and designing of the device, device fabrication and testing of the device have been optimized. The process steps have been established for the fabrication of graphene THz devices viz THz modulator and THz detector.

Graphene THz Modulator

By applying a gate voltage/optical pulse the Fermi level in graphene can be tuned and transmission in graphene channel can be modulated in the THz frequency range. SSPL fabricated different configurations of graphene THz modulators, achieved modulation depth upto 15-23% by electrical gating and 45-55% by optical pumping.

Graphene THz Detector

When steady current flows in the GFET channel, graphene plasmons are generated in the channel which modulates gate and source/drain potential. The potential developed across the graphene channel is directly proportional to the intensity of incident THz beam. SSPL have fabricated graphene THz detectors and achieved responsivity upto 100 mV/W and NEP upto 400 nW/Hz$^{1/2}$.

THz Testing Facility

THz testing arrangement has been created for THz characterization of materials (graphene, MoS_2, InP, LT-GaAs, LT-InGaAs, etc.) and testing of the fabricated THz devices using THz Frequency Domain System (THz-FDS system) and THz Time Domain System (THz-TDS). Detecting THz beam is a challenge because of the low power of the incident THz beam. By using different opto-mechanical components for aligning the weak THz beam and lock-in amplifier, SMUs, etc. THz testing arrangement has been improvised Figure 50, 51.

Fig 50. Fabricated Graphene THz Modulator and Graphene THz Detector

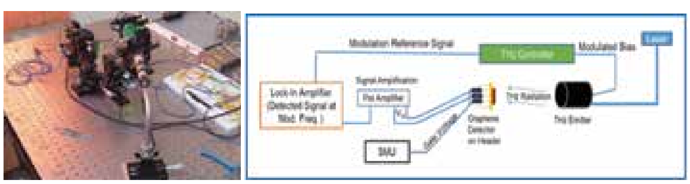


Fig 51. (a) Testing of THz Modulator by Optical Pumping (b) Schematic for Testing THz Detector

Quantum Technologies

Within the last two decades, Quantum Technologies (QT) has made tremendous progress, moving from Noble Prize winning experiments in quantum physics into a cross-disciplinary field of applied research. The field essentially comprises of four domains: Quantum Computation, which employs quantum effects to dramatically speed up certain calculations; Quantum Communication, where individual or entangled photons are used to transmit data in a secure way; Quantum Simulation, where well-controlled quantum systems are used to reproduce the behaviour of other, less accessible quantum systems and quantum sensing where the high sensitivity of coherent quantum systems to external perturbations is exploited to enhance the performance of measurements of physical quantities. The future is quantum and nothing should stand in the way of these quantum technologies becoming the engine of innovations in science, economics and society in the 21st century.

In the last few years, significant technological advancements have been reported in the domain of quantum computing with quantum computers gaining most of the headlines. However, a comparatively less visible and quieter revolution in the world of sensors is also on its way and is just as significant and important. The quantum systems are highly sensitive to external perturbations and while this may prove to be a challenge and prime weakness in quantum computing, the same serves as an advantage while developing 'quantum sensors.' An emerging class of quantum sensors are now being used for measurement of several physical quantities including time, frequency, electric and magnetic fields.

SSPL has initiated the work on Quantum sensors and started the feasibility work for development of Ultra Small Atomic Clock (USAC) and miniaturized atomic magnetometer. Both these atomic devices have tremendous defence application in the area of underwater communication, GPS denied environment, GNSS receivers, etc.

There have been numerous breakthroughs in the scientific and technological use of magnetic fields during the past decades, yet the detection of smallest magnetic fields with highest spatial resolution at room temperature has proven to be a great scientific challenge. The requirement of a lightweight, thermally stable, broad range magnetometer with high spatial resolution may well be met with a quantum magnetometer in the coming years. This includes several military areas where the sensors may be needed, for example, to provide highly accurate positioning data for detection of magnetic anomalies produced by metallic objects such as unexploded ordinance, geophysical structures, vehicles, and ships.

A dramatic change in the military technology landscape can therefore be envisioned in the next few years by the use of these miniaturized magnetometers. The miniaturisation and functionalisation of the proposed magnetometer should significantly impact and disrupt the key applications that benefit from it.

Atomic clocks are among the most accurate time and frequency standards which uses transition of alkali atoms as resonator. For almost a decade, an extensive work has been carried out world-wide to develop the miniaturized version of these atomic clocks generally known as Chip Scale Atomic Clocks. The principle of these miniaturized clocks is based on Coherent Population Trapping (CPT) phenomena which is observed in a compact hermetically sealed silicon vapour cell of few cubic millimetres which is the heart of these quantum sources. These cells having alkali vapours, interrogated by a high-frequency modulated laser beam and signals are analysed.

The frequency stability of such atomic clocks is based on transitions between the hyperfine ground state levels of alkali atoms such as Cesium (Cs) or Rubidium (Rb) whose transition frequencies are 9.91 GHz and 6.64 GHz respectively.

The advanced semiconductor processing, the availability of laser diodes on chip like VCSEL and CPT phenomena made the miniaturization of conventional atomic clock possible with typical short-term stability <1E-11@1000 s and aging rate <1E-8/Year.

Quantum Sensing

Development of Miniaturized Atomic Magnetometer and Miniaturized Atomic Clock

SSPL is working on development of key components of physics package of quantum sensors i.e. VCSEL and Microfabricated AlkaliVapor Cell (MAVC) to demonstrate their miniaturized version with low power budget. VCSEL is required as a pump source for polarisation of Rb or Cs atoms in the vapour cell. This requires wavelength to be matched at D1 or D2 transition frequencies of these atoms. Fabrication of VCSEL is complex technology and requires state of the art infrastructure. SSPL has started working on development of these laser sources under the proposed project on Development of miniaturised magnetometer and will also be suitable for use in atomic clocks too. The tight tolerance required for atomic sensor applications require rigorous Characterization of VCSEL source. A full-fledged Characterization facility is also being set-up at SSPL. The technology once developed will be translated to GAETEC for future production.

MAVCs are sandwiched type structure in which cavities, made of silicon, are sandwiched between two glass plates. These devices are loaded with alkali vapors and buffer gas along with an integrated heater to keep an optimum atomic density.

At SSPL, 1400 µm (1.4 mm) thick, 4" Silicon, P Type <100> substrate which is not a conventional thickness of 4" wafers (500 µm) and in fact 3x times higher has been used. Dual cavity design known as dispensing cavity and optical cavity connected through 150µm deep channel has been used. Hermetical Sealing of Glass/Si/Glass via Anodic bonding has been utilised to fabricate sandwich structure. The incorporation of highly reactive Alkali metals inside deep cavities carried out through solid state route. The first prototype of Cs and Rb alkali vapour cells having a typical die size of ≤ 10 mmx 8mm and cavity volume ≤5 mm^3 in presence of argon as buffer gas has been demonstrated successfully. As a next immediate step, activation of solid-state alkali dispenser pills will be carried out using high power laser and focussing optics. The so obtained alkali vapours inside the cavity will be analysed through spectroscopic measurements whose setup are getting ready at SSPL. SSPL will also put emphasis on Physics Package development using mostly indigenous optical/ mechanical components. Miniaturized control electronics and software development will be done through an Indian Industry to support indigenous development to a large extent At present, the first prototype demonstration of Silicon Alkali Vapour Cell is done at SSPL. Once the system is developed, ready and successfully demonstrated, India will be one of the leading countries for in-house quantum sensing technology.

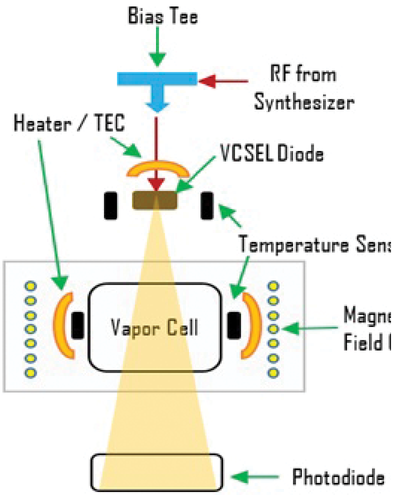


Fig 52. Schematic of Physics Package

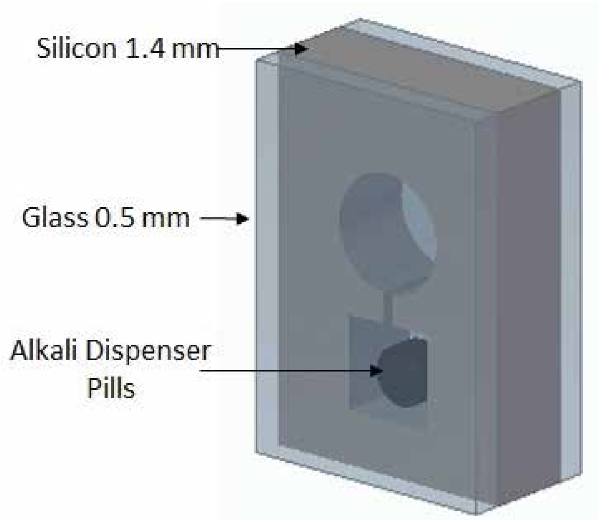


Fig 53. Schematic of Silicon-based Alkali Vapour Cell

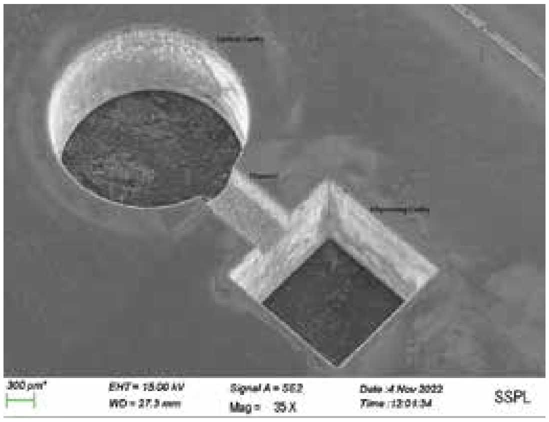


Fig 54. mm Deep Cavity by Laser Milling

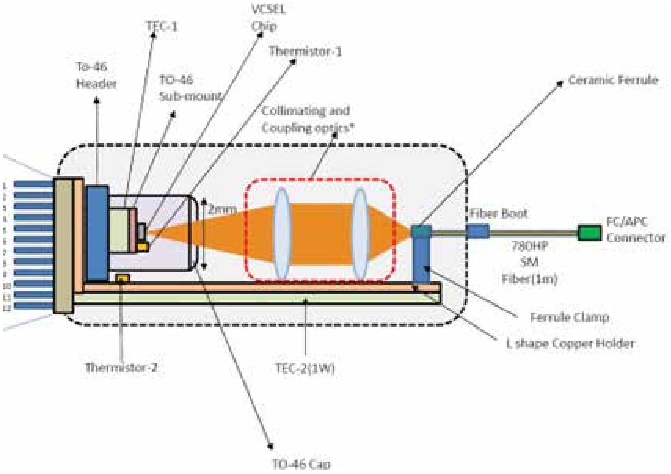


Fig 55. Targeted Structure of VCSEL Module

Fig 56. First Prototype Demonstration of Silicon Alkali Vapour Cell