Form 1

2019 Report Form for Collaboration with Research Center for Biomedical Engineering

Year/month/date	
Number	

Date /Month/Year

date: 16/03/2020

To Chairman, Board of Directors, Research Center for Biomedical Engineering

Applicant

Affiliation School of Mines and Metallurgy, Kazi Nazrul University

Title Assistant Professor

Name Arindam Biswas Arindam Biswas

Address School of Mines and Metallurgy, Kazi Nazrul University, Asansol West Bengal, Pin-713340, India

Phone +91-9932311710

Fax +91-341-2271024

E-mail mailarindambiswas@yahoo.co.in

Report Form for Collaboration Research

Research Theme	Study on Biomedical THz Imaging based on Wide Band Gap Semiconductor IMPATT Source
Research Area	1. Biomaterials 2. Bioengineering 3. Functional molecules 4. Chemistry/Electrical Engineering/Mechanical Engineering/Materials Science
Research Period	From: Date/month/Year To: Date/month/Year 01/06/2019 ~ 31/03/2020

Applicant Organization			
Name	Department	Title	Role
Amit Banerjee	Microelectronic Technologies & Devices, Department of Electrical and Computer Engineering, National University of Singapore, 21 Lower Kent Ridge Rd, Singapore 119077,	Scientist ER	Detector Design, Biomedical Characterization
Aritra Acharyya	Department of Electronics and Communication Engineering, Cooch Behar Government Engineering College, Cooch Behar, West Bengal, India	Assistant Professor	Design and Development of WGP based GaN IMPATT
Jitendra Nath Roy	Dept. of Physics, Kazi Nazrul University, Asansol , West Bengal, Pin-713340, India	Professor	Design and Development of WGP based GaN IMPATT

Parth Pratim Sarkar	Department of Engineering and Technological Studies, University of Kalyani, Kalyani, Nadia, West Bengal, India	Sr. Scientific Officer	THz Antenna Integration Simulation

Collaboration Partners in the Research Center	Hiroshi Inokawa Hiroaki Satoh Research Institute of Electronics, Shizouka University, Japan

Research Results (Including Purpose, Results, Figures, etc.)

Optimized design parameters such as thickness and doping densities of different layers of n^+-n-p-p^+ structured double-drift region GaN IMPATT diode designed to operate at 1.0 THz is already reported by the authors. Comprehensive simulation studies have already provided the estimation of power delivery capability, parasitic series resistance and noise performance of the optimized source at 1.0 THz. However, it is well known fact that the realization of the optimized structure is a tricky job by considering the state-of-the-art GaN fabrication technology. Especially, achieving the absolute value of doping density of *n*- and *p*-layers is almost unrealistic task. Therefore, it is very important to acquire the knowledge about how much extent the power output, series resistance and noise measure of the source are affected due to the change in doping level of both *n*- and *p*-layers. In this present study, the sensitivities of the above-mentioned parameters with respect to the change in the doping densities of *n*- and *p*-layers.

1. Structure and Fabrication Issues

The realization of wide bandgap semiconductor material based avalanche transit time sources is a very attractive area of research to the researchers working since last two decades in order to find a high power, low noise solid-state source at terahertz frequency regime (0.30 – 10.0 THz). Among different wide bandgap materials like SiC, GaN, diamond, etc., GaN is the most potential material for realizing high frequency, high power, low noise semiconductor devices. The proposed structure of the DDR GaN IMPATT diode is shown in Figure 1 (Biswas et al., 2018; Chakraborty et al., 2019). It is well known fact that the realization of the optimized structure is a tricky job by considering the state-of-the-art GaN fabrication technology. Especially, achieving the absolute value of doping density of *n*- and *p*-layers is almost unrealistic task. Therefore, it is very important to acquire the knowledge about how much extent the power output, series resistance and noise measure of the source are affected due to the change in doping level of both *n*- and *p*-layers.

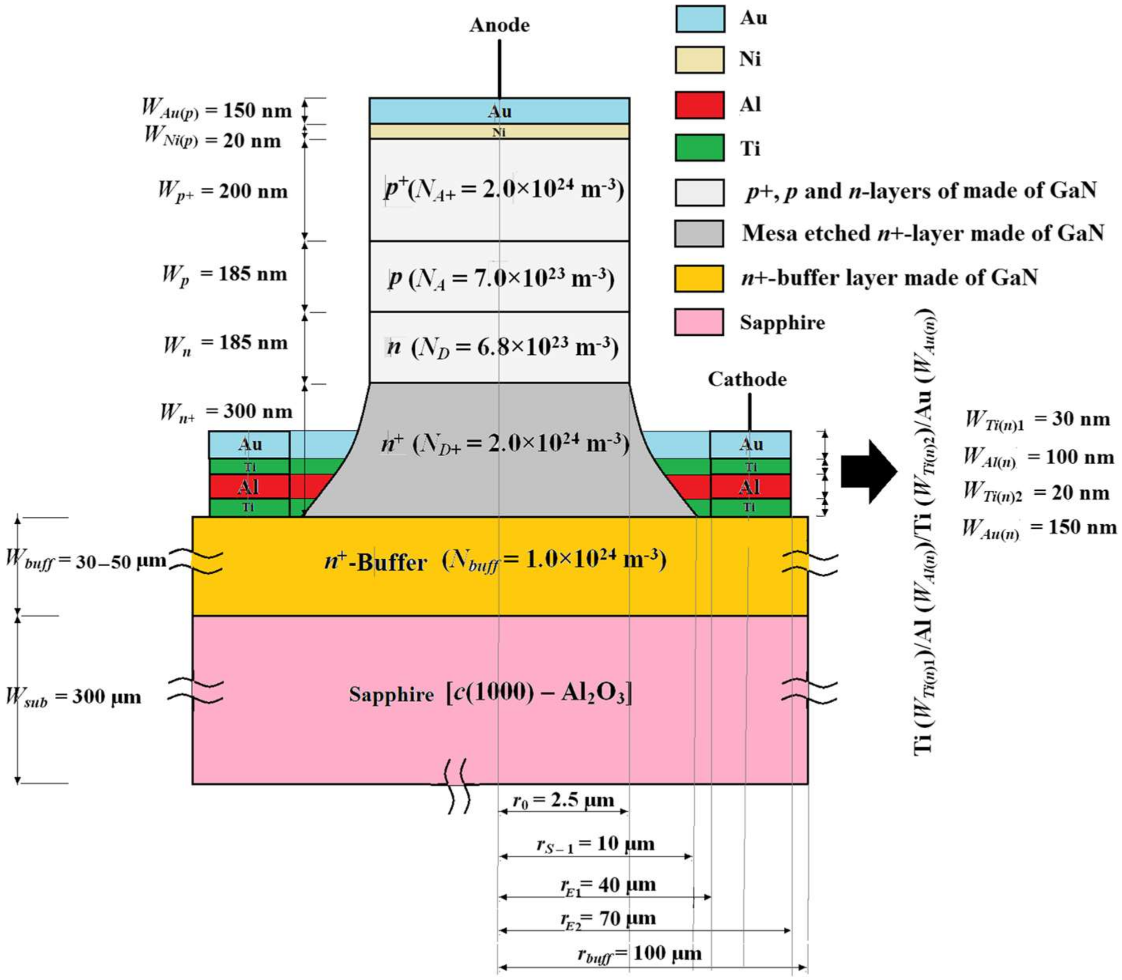


Fig. 1. GaN IMPATT structure for 1.0 THz operation.

2. Results

The doping concentrations of both *n*- and *p*-layers are assumed to be varied between $\Delta N = \pm 10\%$ of the optimized values, i.e. ±10% of 6.8×10^{23} and 7.0×10^{23} m^{-3} respectively, and the structure is re-simulated in order to study the aforementioned effect. The Fig. 2 illistrates the sensitivity analysis results. Maximum 21.9% of change in power output is observed. It is observed that the power output is increased with the decrease of doping levels. Sharp increase in power output is observed just after the device enters to the punch-through region. Sharp decrease in series resistance is observed after the device become punch-through for lower doping density of *n*- and *p*-layers. Noise measure is slightly increased with the decrease of doping density of *n*- and *p*-layers.

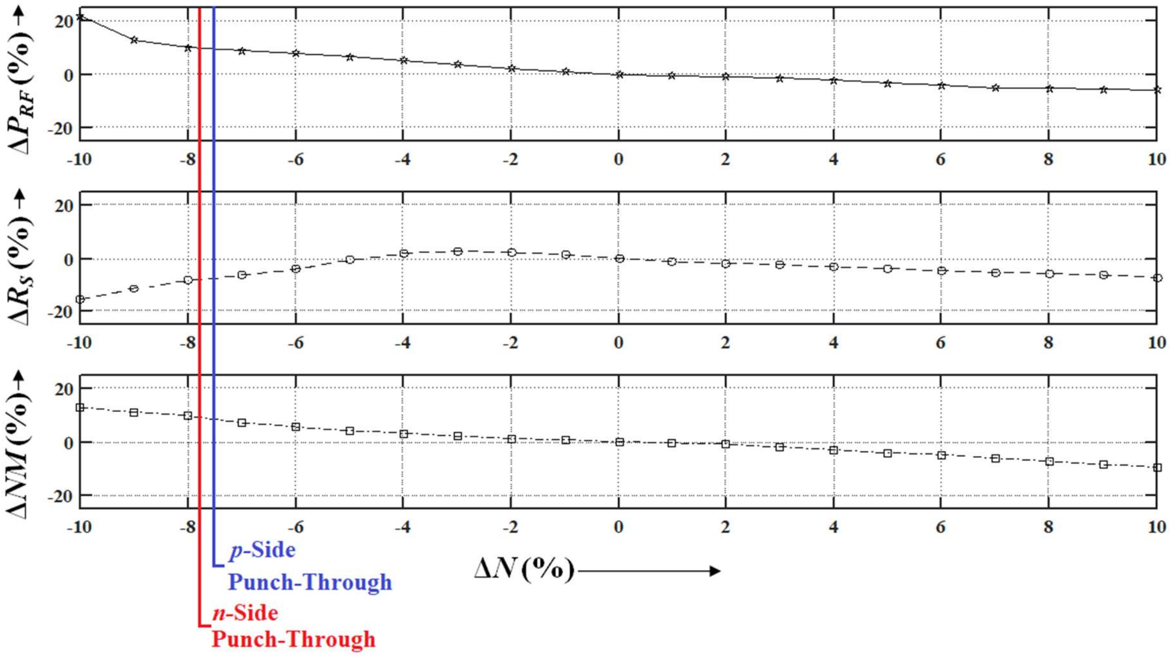


Fig. 2. Variations of percentages of change in power output, series resistance and noise measure with the percentage of change in doping density of *n*- and *p*-layers.

List of Publications Related to the Collaboration Research
NIL

Li st of Presentations (Conference, Meeting, etc)
1)Arindam Biswas, Aritra Acharyya, Kazuki Hirai, Hiroaki Satoh, Hiroshi Inokawa, "1.0 THz GaN IMPATT Source: Influence of Change in Epitaxial Doping Concentrations," Annual Meeting for 2019 Cooperative Research at Research Center of Biomedical Engineering (Communicated, Mar. 13, 2020). 2) Arindam Biswas, Aritra Acharyya, Hiroaki Satoh and Hiroshi Inokawa, "Study on high-power terahertz sources based on GaN IMPATT diode," Symposium on Frontier of Terahertz Science VI, Con6, p. 43 (Tokyo Institute of Technology, Japan, Nov. 28-30, 2019) [in Japanese]

List of Awards
NIL

Registration of research-theme continuation for next year Prior consent from the collaboration partner in the Research Center is necessary.	Yes	No
Research plan for the next year (from April 1, 2020 to March 31, 2021), if the collaboration research is continued.		

The entire project can be divided into six primary developmental steps; those are given by

(A) Design and Fabrication of the Seed IMPATT diode Structure,

(B) Bonding and Packaging,

(C) Resonant-Cap Cavity for THz IMPATT Source,

(D) Broadband Oscillator Realization,

(E) Source-Antenna Integration, and

(F) Power Combining.

All the important issues related to each of the abovementioned steps are discussed below.

(A) Design and Fabrication of the Seed IMPATT diode Structure

Design and simulation of GaN based DDR IMPATT seed structure (Figure 1) for 1.0 THz frequency generation has already been carried out. Doping and thickness of different layers of the DDR structure are already chosen subject to obtain maximum DC to RF conversion efficiency. The metal contacts for both anode and cathode have been confirmed via technical discussion with our research group as well as by acquiring knowledge from the published literature. All details regarding the proposed DDR structure and its large-signal performance have been already published [1]. However, after several discussions with the Japan research group, some issues have risen regarding the proposed structure; those are point-wise briefed here.

1. Instead of using Sapphire [c(1000)-Al_2O_3] as the substrate for growing the entire DDR structure, it can be grown on GaN substrate. Primary advantage of homo-epitaxial growth over the hetero-epitaxial growth is reduction of dislocation at the interface of substrate and grown layer. Moreover, better thermal conductivity of GaN than Sapphire enables the GaN substrate to act as an internal heat sink.

2. Since the efficiency of the THz diode is expected to be smaller than 10%; therefore large amount of heat energy supposed to be dissipated within the diode during its continuous wave steady-state operation. This will lead to thermal runway of the diode. In order to avoid this thermal issue, an external heat sink (having cylindrical shape) preferably made of type-IIa diamond (thermal conductivity ~1200 W m^{-1} K^{-1}) has to be attached below the substrate layer (Figure 2 (a)) of the diode chip by using appropriate adhesive substance (having high thermal conductivity) [2-4]. The temperature distribution inside the type-IIa diamond heat sink is shown in Figure 2 (b).

3. Proposed structure may face electric field crowding effect which may lead to the edge (local) breakdown or premature breakdown. We have to incorporate necessary structural modification in the device structure in order to avoid such premature breakdown.

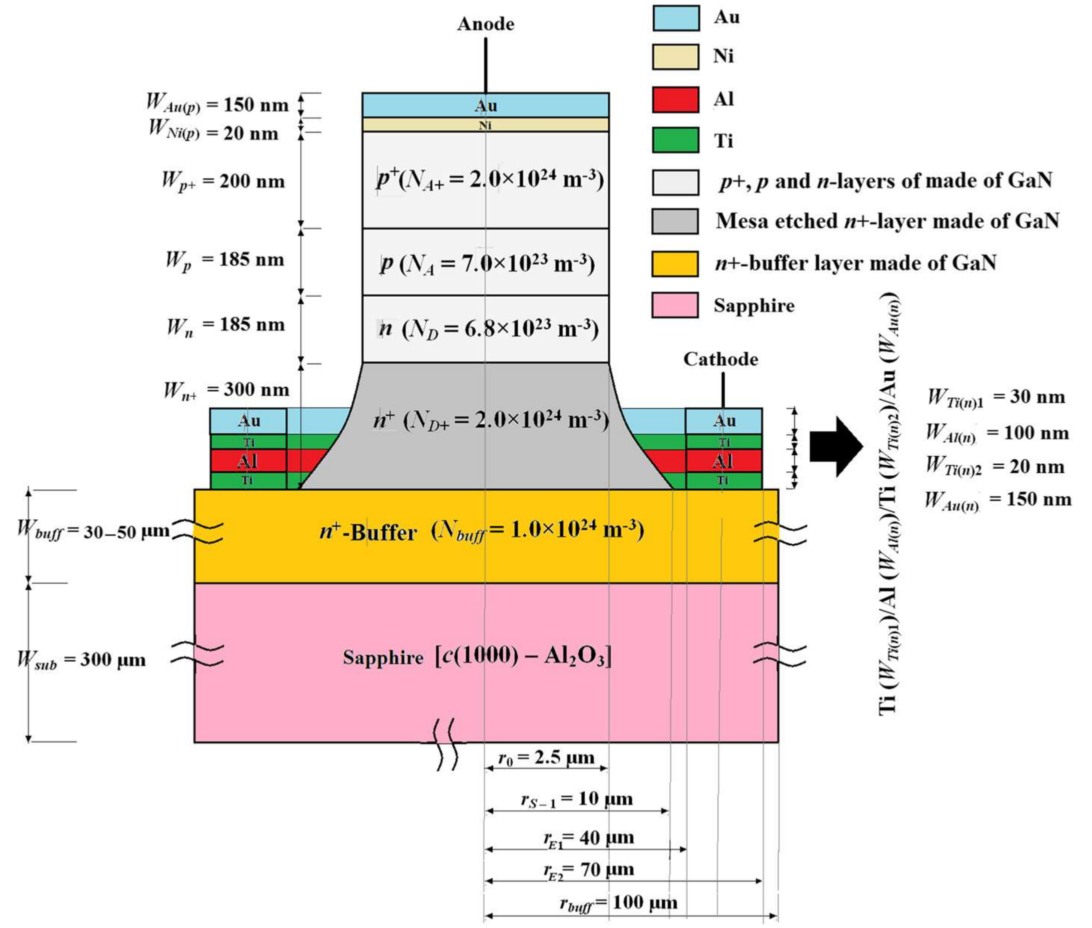


Figure 1: Schematic diagram showing the vertical section of the 1.0-THz GaN DDR IMPATT structure grown on sapphire substrate.

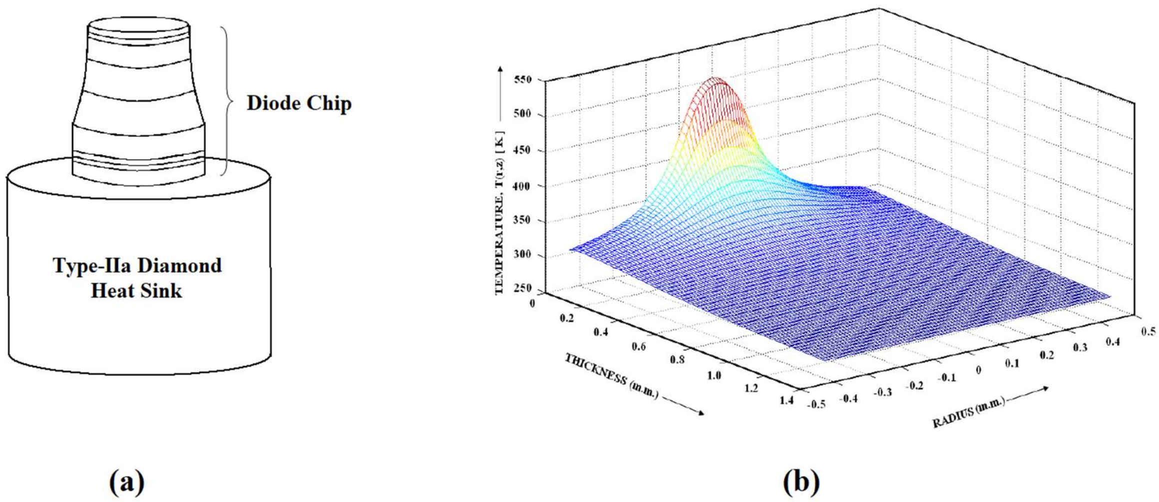


Figure 2: (a) Diode chip attached on a cylindrical shaped type-IIa diamond heat sink, and (b) temperature distribution inside the heat sink for steady-state thermal operation at 500 K [2].

After finding the appropriate solutions for the abovementioned three issues, the bonding and packaging issues will have to be taken into consideration.

(B) Bonding and Packaging

Wire bonding of anode and cathode terminals of the diode has to be done with the S4 package. Wire bonding of the anode can be done by following the conventional wire edge boding technique. Middle portion of a 5 – 10 μm diameter gold wire can be bonded on the top of the diode chip (anode) by thermal sonic compressor and both ends of the gold wire can be connected with gold coated ring-cap (package anode) of the S4 package by using silver epoxy baked at 150^0C for half an hour. The diode chip attached with external type-IIa diamond heat sink has to be die bonded to gold coated copper cylinder at the lower surface of the S4 package; it will act as integral heat sink along with the diamond heat sink. However, the bonding of the cathode with the gold coated copper cylinder (package cathode) is a tricky job. We have to find out the probable procedure for this. Figure 3 shows the bonding and packaging of the diode chip in a S4 package. Both anode and cathode of the diode chip have to be bonded with gold coated cap and gold plated copper cylinder respectively by using multiple numbers of gold wires in order to reduce effective parasitic series resistance; however, only single wire bonding is shown in Figure 3. After packaging, the overall equivalent circuit of the packaged diode is shown in Figure 4. Here, L_p and C_p are the package inductance and capacitance, $-R_D$, C_D and R_S are the diode negative resistance, capacitance and parasitic series resistance (all are functions of frequency).

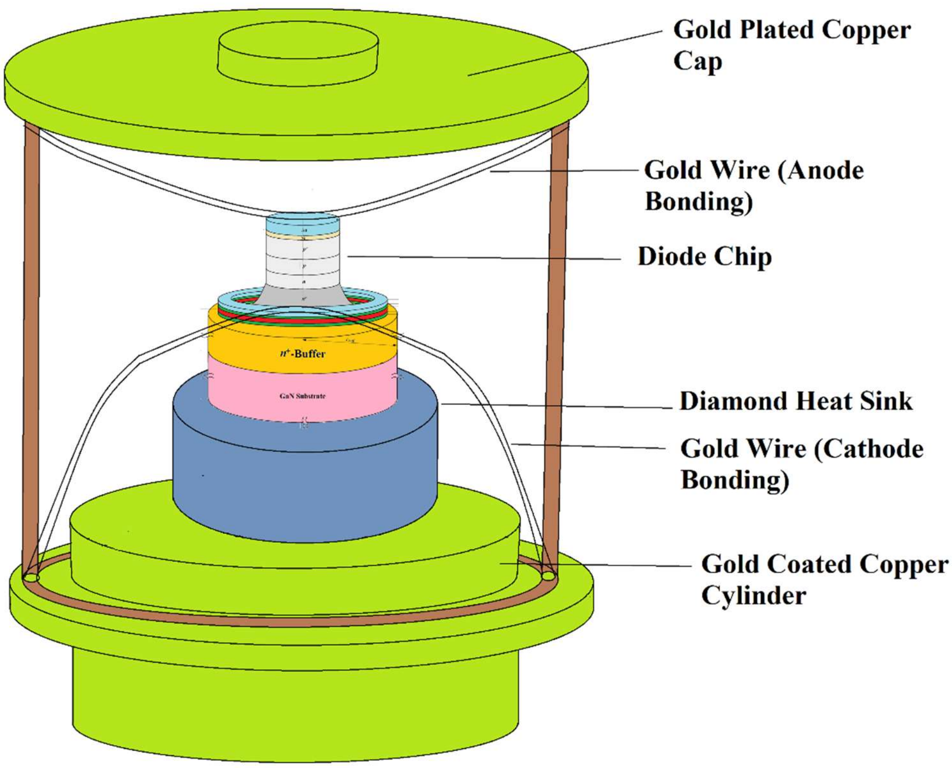


Figure 3: Schematic illustrating the bonding and S4 packaging of the diode chip.

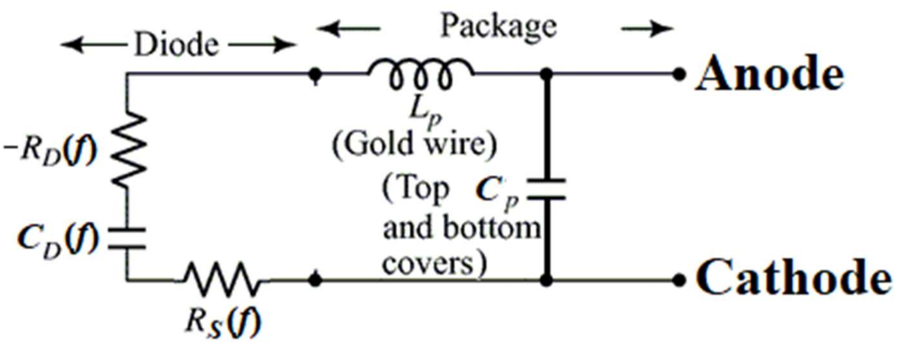


Figure 4: Equivalent circuit of the S4 packaged IMPATT chip.

At THz regime stud-type package may be the better option as compared to the S4 package [5]. We are still searching for the best package for THz IMPATT diode.

(C) Resonant-Cap cavity for THz IMPATT Source

The packaged diode has to be embedded in an appropriately designed rectangular waveguide cavity resonator as shown in Figure 5. The diode has to be reverse-biased and may be embedded inside the cavity via a bias post as shown in Figure 5. The packaged diode mounted inside the suitable cavity resonator (circuit) leads to device-circuit interaction which results oscillation. The magnitude of the overall negative resistance of the packaged diode designed to operate at 1.0 THz is very small, in the orders of 0.1 – 1.0 Ω [1]. On the other hand, the real part of the circuit impedance of the cavity resonator (resonant frequency f_r = 1.0 THz) remains in the order of 100 Ω. Therefore, a huge impedance mismatch is expected at this point and very inefficient power transfer can occur from diode to the resonator. The impedance matching between device and circuit can be achieved by using two possible methods. Those are

1. By using reduced height waveguide cavity, and

2. By using resonant-cap cavity.

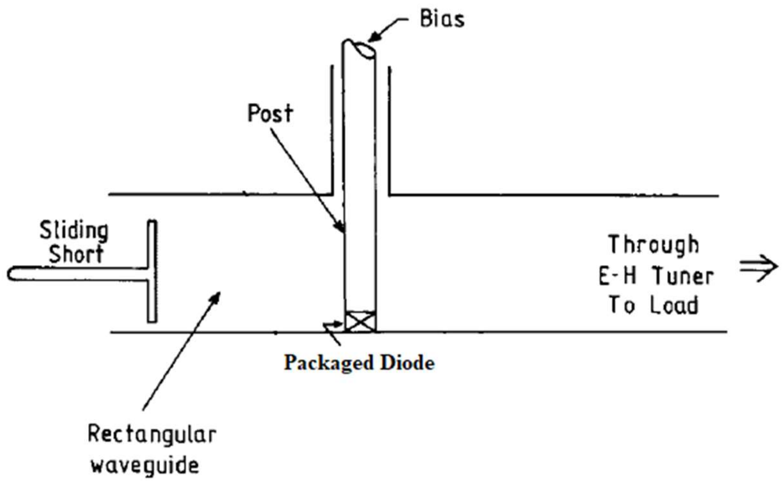


Figure 5: Schematic of the packaged diode embedded inside a rectangular waveguide cavity resonator via a bias post.

First method may be suitable for microwave/millimetre frequency range up to even 94 GHz. However, to match impedance from reduced height waveguide in which the diode is mounted need to be matched with the full-height waveguide system either with stub matching or stepped impedance/exponential taper transformer. But for higher millimetre-wave frequencies and THz (0.3 – 10 THz) range it is impractical to use post-mounting technique. Thus at the THz frequency range, resonant-cap cavity using disk-cap resonator circuit is the best choice for impedance matching at THz regime [6, 7].

In a resonant-cap cavity type source, the packaged diode is embedded in a high-Q resonant-cap cavity and two together are mounted in a rectangular waveguide through which the source is connected to the load as shown in Figure 6 [6]. The disk of the resonant-cap and the bottom broad-wall of the rectangular waveguide form the cap cavity, which is equivalent to a radial transmission line causing efficient power transfer from the device to the load [8]. The diameter of the disk must have the dimension $D = (\lambda_r/4 + m\,\lambda_r/2)$, where λ_r is the resonant wavelength and m = 0, 1, 2, 3, …… [8]. By choosing suitable value of m, appropriate cap-cavity structure can be designed.

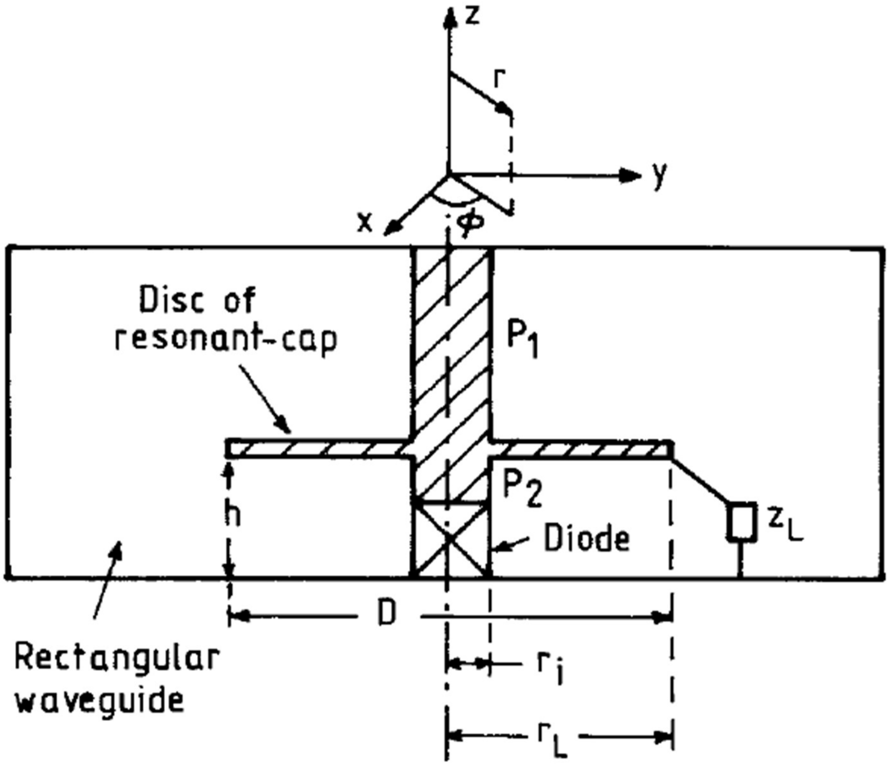
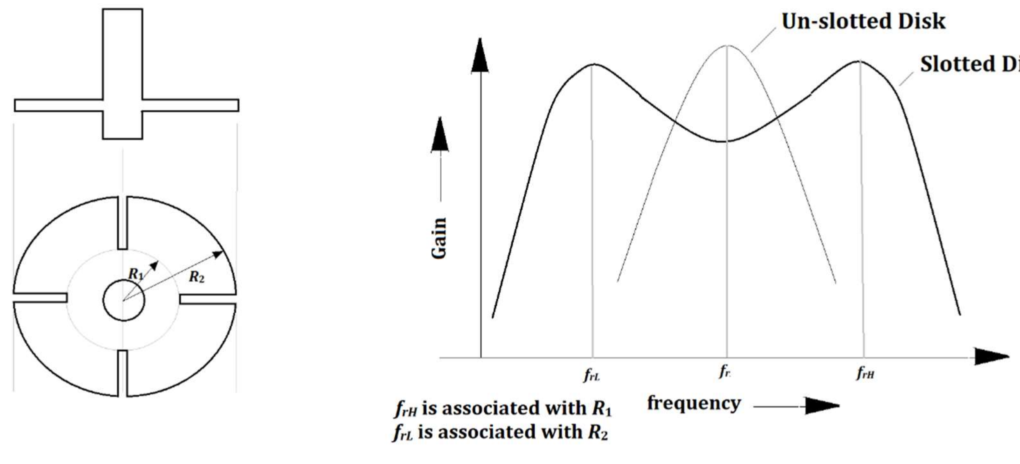


Figure 6: Schematic of a resonant-cap based source with the devices embedded in the resonant-cap cavity [6].

(D) Broadband Oscillation

The disk can be made slotted (Figure 7) in order to increase the bandwidth of the cap-cavity oscillator [9 -12].



(a) (b)

Figure 7: (a) Side and top views of slotted disk structure, and (b) frequency response of slotted and un-slotted disk structure together with the bottom broad-wall of the waveguide.

(E) Source-Antenna Integration

The radial transmission line structure itself can behave like an integral antenna for the THz IMPATT source. Its principle of working may be understood in terms of modelling it like a microstrip antenna. Its major radiation lobe will be along the direction of z-axis as shown in Figure 8. However, the bias feeding point to the packaged IMPATT will have to be decided (bias post should not interfere with the major lobe) in order to obtain best radiation efficiency.

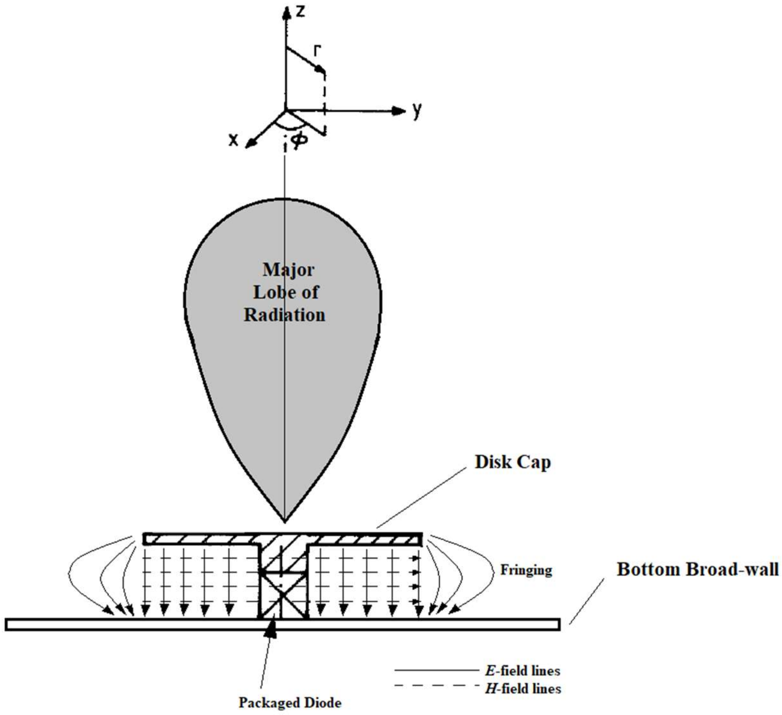
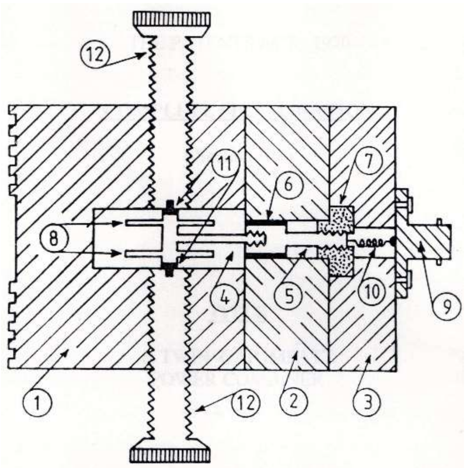


Figure 8: Radial transmission line structure for source-antenna integration.

(F) Power Combining

THz power output from a single source may be very small (practically < 10 mW). Therefore, suitable power combining of multiple sources must be implemented in order to enhance the radiated THz power. Twin-cap IMPATT power combining technique [13], vide Fig. 9, may be used that may be optimized for phase coherence using some form of Meta-surface too.



PARTS LIST

(1,2,3) Copper blocks, (4) Rectangular waveguide cavity, (5) Bias filter, (6) Insulating material, (7) Insulating guard-ring (8) Twin-cap structure, (9) BNC connector, (10) Gold spring, (11) IMPATT diode, (12) Threaded diode holder.

Figure 9: Twin-cap IMPATT power combiner [13].

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