Journal of Physics Through Computation (2019) Vol. 2: 9-16 **DOI: 10.23977/jptc.2019.21003**
Clausius Scientific Press, Canada **ISSN 2617-1163**

Design & Analysis of a Terahertz Power Source for a Non-invasive, Non-ionizing Imaging of Full Body Prosthetics: A Novel Technique

Saikat Adhikari[1,a], John LaRocco[2,b], Rajdeepta Saha[3,c] and Moumita Mukherjee[1,d,*]
[1]*Adamas University, Kolkata, India*
[2]*Volunteer Researcher, Singapore, Singapore*
[3]*Camellia Institute of Engineering and Technology, MAKAUT, India*
[a]*spgrar@live.com*, [b]*johnlarocco@gmail.com*, [c]*rajdeepta2015@gmail.com*, [d]*mm.adamasuniv@gmail.com*
**corresponding author*

Keywords: FBP, Solid State T-Ray Source, Non Linear large signal analysis, GaN/AlN Superlattice, Room Temperature T-Ray Radiation System, Radiation Thermographs.

Abstract: The authors have designed and studied the superlattice terahertz device for accurate detection of cancer cell in a Full Body Prosthetic (FBP). For this a generalized non-linear simulator is developed. The model predicts that identification of cancerous cell within FBP could be done satisfactorily by analyzing corresponding thermographs. For T-Ray source and detector the authors have considered p^{++} -n^{-} - n - n^{++} type Mixed Tunneling Avalanche Transit Time (MITATT) Device at 0.1 THz. The study reveals that the proposed device is capable of developing 10 W level of fundamental harmonic power at around 100 GHz. The simulator incorporates the physical and electrical properties of GaN/AlN supperlatice, which include temperature and field dependent carrier ionization rates, saturation velocity of charge carriers, mobility, inter-sub band tunneling and drift velocity overshoot effects as well as hot carrier effects inter-band scattering of electron hole pairs in superlattice region. An equivalent circuit model is developed and analyzed for obtaining impedance and admittance characteristics. To the best of authors' knowledge this is the first report on large signal modeling of THz Solid State imaging unit for thermo graphic analysis of malignant tumors in Full Body Prosthetics (FBP).

1. Introduction

The terahertz region (1THz= 10^{12} Hz) lies in between the microwave and infrared regime of electromagnetic spectrum. This has now become a promising area of R&D activities in the diversified field of Physics, Chemistry, Engineering, and Medical & Biological Sciences. The unique property of T-Ray is it's low photon energy which intern is beneficial for medical applications owing to it's non-ionizing nature. The presence of malignancy in human blood cell causes increase in tissue water content. This acts as a contrast in T-Ray imaging. In spite of it’s huge application possibilities, the Biomedical Instrument Industries are still lagging in full utilization of this range of EM Spectrum for the non-invasive & non-hazardous imaging of human body. This is because the lack of suitable room temperature and compact sources and detectors. Most of the available T-Ray sources are bulky & low temperature and therefore not suitable for Biomedical applications. Considering the ever growing need of the development of T-Ray sources for biomedical purpose, the authors have proposed a new class of solid state room temperature device that can be used as a potential T-Ray source for the identification of malignant tumors in organ placed in a Full Body Prosthetic (FBP) arrangement.

A full-body prosthetic (FBP) is an artificial system holding the life support system for an isolated brain or transplanted head. Due to the experimental nature of artificial organ technologies, an artificial body could be designed to house biological organs from a donor. A non-invasive and safe method of bio-medical scanning would be essential to reduce the risk of infection and structural weakness if the FBP’s internal system is exposed. The terahertz band lies between the microwave and infrared regions of the electromagnetic spectrum and the radiation has very low photon energy and thus it does not pose any ionization hazard for biological tissues. The radiation has unique absorption spectra due to intermolecular vibrations in this region that have been found in different biological materials. This has made terahertz imaging very attractive for medical applications in order to provide complimentary information to existing imaging techniques. In order to test the viability of terahertz imaging for an FBP, a thorough investigation will be constructed. Healthy and malignant cells will be incorporated under various conditions inside an FBP. In addition to being relevant to detecting tumors in FBP, the findings could also be useful in analysis of customized bioreactors for the pharmaceutical and biotechnology industries.

The present paper will report (i) Design and Characterization of an exotic Avalanche Transit Time (ATT) device for T-Ray generation, (ii) Design of a suitable T-Ray radiation system; (iii) T-Ray imaging snap shots of malignant tumor located in a specially designed FBP. The authors have designed an ATT device where carrier generation is contributed by both Avalanche multiplication and inter-band tunneling phenomenon. The resultant device will operated in MITATT (Mixed Impact-ionization Tunneling ATT) mode and corresponding power generation will be in THz frequency regime. The proposed structure is a Hexagonal Wz-GaN/ AlN super lattice of periodicity four with asymmetrical doping and width distribution in the active region of the device. Super lattice configuration with asymmetrical doping density in active region results in spatial separation of mobile charges (electrons & holes) within the active region of MITATT device. This improves the electrical properties such as carrier life mobility and life time significantly. The inter-sub band transition and drifting of carriers through the active region of the device induces a current pulse in the external circuit and the said transition generates an oscillation frequency in THz region. The authors have earlier developed a self consistent, generalized large signal simulator for the realistic modeling and analysis of ATT devices, published elsewhere [1-2]. The present study has used that indigenously developed simulator with some important modification considering the various quantum aspect of carrier transition in asymmetrical super lattice structure. Quantum modified Classical drift diffusion model is used for solving Poisson and current continuity equations subject to appropriate boundary conditions [3].The validity of the model is established by comparing the simulated data with experimental findings.

Substantial research work has already been done with Wide Band Gap (WBG) semiconductor based ATT devices in recent years [1-2]. Most of the research works are focused on IMPATT mode of operation with flat doping profile. The said studies have established the superiority of WBG GaN, SiC and Si/SiC materials for generating THz power with a moderate to low efficiency[1-2]. However, to the best of authors' knowledge asymmetrical super lattice ATT devices are not available in current literature. High frequency oscillation from a power device needs high mobility of carrier in transit. Specially designed Super lattice structure is quite promising from this aspect; this has made the authors prompted to choose such exotic doping profile for designing a room-temperature and efficient power source at Terahertz region.

Wide band gap materials (III-V and IV-IV compound semiconductors) are promising for developing high power efficient ATT devices. Power output from an ATT device depends upon the saturation velocity and critical electric field at breakdown of the base semiconductor. GaN and AlN, having saturation velocity ~ $2x10^5$ m/s, critical breakdown field ~ $2x10^8$ V/m, are expected to be a potential pair for developing a superlattice structure. The inherent mobility of AlN/GaN reduces transit time of carriers through the active region of the device. This makes the device suitable for oscillating at THz (0.1 THz to 10 THz) frequency region. Moreover the lattice mismatch in between sapphire substrate and epilayer AlN/GaN is minimum compared to flat GaN epilayer [4]. Thus the authors have chosen AlN/GaN superlatice for designing the high power, high frequency ATT device.

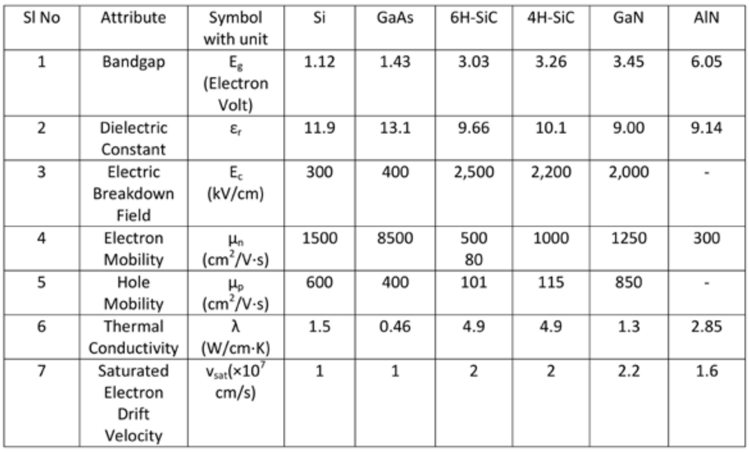
Worldwide physicians are concerned for early diagnosis of malignancy in human body so that patient's life could be saved. Most of the non-invasive imaging techniques, available now-a-days, rely upon X-Ray. However X-Ray is ionizing radiation and it's a secondary cause of cancer. Moreover early detection of malignant tumor is the biggest unsolved problem as X-Ray could only detect tumor of considerable dimension. T-Ray, on the other hand, is non ionizing and expected to identify malignant tumor of less than 1mm diameter. This possibility is thoroughly investigated by the authors in the present paper by designing a FBP system with malignant and non malignant cell/ tissues tumors of various dimensions. COMSOL multiphysics based RF module and heat transfer module are used for this.

2. Methodology:

This part will deal with the simulation methodology, necessary boundary conditions and the device structure details.

2.1. Quantum Modified Non-Linear Drift-Diffusion (QMNLDD) model

TABLE I. MATERIAL PARAMETERS OF DIFFERENT SEMICONDUCTORS



Sl No	Attribute	Symbol with unit	Si	GaAs	6H-SiC	4H-SiC	GaN	AlN
1	Bandgap	E_g (Electron Volt)	1.12	1.43	3.03	3.26	3.45	6.05
2	Dielectric Constant	ε_r	11.9	13.1	9.66	10.1	9.00	9.14
3	Electric Breakdown Field	E_c (kV/cm)	300	400	2,500	2,200	2,000	-
4	Electron Mobility	μ_n (cm^2/V·s)	1500	8500	500 80	1000	1250	300
5	Hole Mobility	μ_p (cm^2/V·s)	600	400	101	115	850	-
6	Thermal Conductivity	λ (W/cm·K)	1.5	0.46	4.9	4.9	1.3	2.85
7	Saturated Electron Drift Velocity	v_{sat}($\times 10^7$ cm/s)	1	1	2	2	2.2	1.6

The quasi 3D vertical and asymmetrically doped AlN/GaN-*ATT* **(**p^{++} -n- - n^+ - n^{++} doping profile) T-Ray source and detector have been designed and analyzed in the paper. The physical properties of AlN/GaN material along the symmetric axis of the device are summarized in Table 1. The authors have made non-linear Large-signal (L-S) simulation in order to get realistic view of the device characteristics under various operating conditions. At each instant of time the physical properties such as electric field, electron and hole current components, recombination current are obtained by solving the non-linear field and carrier transport equations, i.e. Poisson’s equation and combined current continuity equations for various modulation factors at the edges of the active region, subject to satisfaction of appropriate boundary conditions. The authors have considered the effect of introducing a n-bump layer of appropriate doping concentration in between the substrate and epi-layer.

$$\frac{\partial^2}{\partial x^2}V(x,t) = -\frac{q}{\varepsilon}[N_d(x,t) - N_a(x,t) + C_p(x,t) - C_n(x,t)] \qquad (1)$$

$$\frac{\partial}{\partial x}p(x,t) = -(\frac{1}{q})\frac{\partial}{\partial x}J_p(x,t) + G_p(x,t) - R_p(x,t) \qquad (2)$$

$$\frac{\partial}{\partial x}n(x,t) = (\frac{1}{q})\frac{\partial}{\partial x}J_n(x,t) + G_n(x,t) - R_n(x,t) \qquad (3)$$

$$J_p(x,t) = -q\mu_p[C_p(x,t)\frac{\partial}{\partial x}V(x,t) + (\frac{K_B T_j}{q})\frac{d}{\partial x}C_p(x,t)] \qquad (4)$$

$$J_n(x,t) = -q\mu_n[C_n(x,t)\frac{\partial}{\partial x}V(x,t) - (\frac{K_B T_j}{q})\frac{d}{\partial x}C_n(x,t)] \qquad (5)$$

$$J_t(x,t) = J_n(x,t) + J_p(x,t) \qquad (6)$$

Where $J_{p,n}(x,t)$ is the electron and hole current density, $V(x,t)$ is the electric potential, $J_t(x,t)$ is the total current density, $C_{p,n}(x,t)$ is the charge carrier concentration, $G_{p,n}(x,t)$ is the carrier generation rate, $R_{p,n}(x,t)$ is the carrier recombination rates, $N_a(x,t)$ and $N_d(x,t)$ are the electron and hole current density , $\mu_{p,n}$, ε , T_j are the mobility of charge carriers, permittivity, junction temperature respectively.

The carrier generation rates are obtained due to the avalanche phenomenon and band to band tunneling of electron and hole. It can be written as-

$$G_{p,n}(x,t) = G_{A_{p,n}}(x,t) + G_{T_{p,n}}(x,t) + G_{ph_{p,n}}(x,t) \qquad (7).$$

In the above equations, $G_{A_{n,p}}(x,t)$, $G_{T_{p,n}}(x,t)$ and $G_{ph_{p,n}}(x,t)$ represent the avalanche and tunneling carrier generation rates and photo-generation rate respectively. The avalanche carrier generation rates for electron and hole can be expressed as -

$$G_{A_p}(x,t) = G_{A_n}(x,t) = \alpha_p(x,t)v_p(x,t)C_p(x,t) = \alpha_n(x,t)v_n(x,t)C_n(x,t)$$

Where, $\alpha_{p,n}, v_{p,n}$ are the ionization-rate and drift velocities of the charge carriers respectively.

The electron tunneling generation in GaN/AlN is expressed as

$$G_{T_n}(x,t) = a_T E^2(x,t)\exp[1 - \frac{b_T}{E(x,t)}] \cdot$$

Where, $E(x,t)$ represents the electric field. The coefficients a_T and b_T can be determined by-

$$a_T = \frac{q}{8\pi\hbar^2}(\frac{m_n^*}{E_g})^{\frac{1}{2}}, b_T = \frac{1}{2q\hbar}(\frac{m_n^* E_g}{2})^{\frac{1}{2}}$$

where, E_g is the band gap energy introduced in AlN/GaN superlattice by means of doping, m_n^* is the effective mass of electron , $\hbar(\frac{h}{2\pi})$ is the normalized Planck's constant, q (1.6 x 10^{-19} C) is charge of the electron and h (6.625 x 10^{-34}) is the Planck's constant. The tunnel induced hole generation rate can be expressed as- $G_{T_p}(x,t) = G_{T_n}(x',t)$. The tunnel induced hole-generation rate at x is the function of electron generation rate due to tunneling at x' .Where, $(x - x')$ is the spatial separation in between valance and conduction band at the same energy level. It can be obtained from the energy band diagram of p^{++} -n- - n^+ - n++ device.

2.2. Simulation of FBP Model

Comsol Multiphysics Simulator is used for designing an equivalent FBP model with cylindrical geometry. The dimension of the Cylinder is as follows:
120 mm in length and 50 mm in diameter.

2.3. Comsol Thermographic model of T-Ray Radiation System

Comsol Multiphysics Electromagnetic Module is used for designing T-Ray radiation system and corresponding generation of thermographs. Hyperthermic oncology and relevant models coupled with EM Modules that include bio heat equations are used for this purpose. The model takes the advantage of rotational symmetry which intern allows modelling in quasi 3D cylindrical coordinates with an appropriate selection of fine meshing to achieve excellent accuracy. The model uses frequency domain formulation. T-Ray radiation source/ antenna is embedded in a FBP along it's axis. Initially the FBP is considered to be filled with non-malignant cell and thereafter with malignant cell of appropriate permittivity and thermal conductivity values. The radiation coming out from the source has been absorbed by the surroundings cells and generates heating effects according to the electrical properties of malignant/ non malignant cells. Due to the more water contains in malignant cell compared to its non malignant counter parts, thermal gradient would vary considerably and the authors have accurately studied the corresponding thermographs to detect the presence of malignant cell in FBP. In addition to heat transfer equation the model computes cell damage integral as well. The T-Ray radiation source distribution decays gradually as a function of distance from the source. The authors have considered the electrical and thermal properties of malignant and non malignant cells from published literature [5]

3. Result and Discussion

Fig-1 depicts the admittance characteristics of the simulated T-Ray source for different operating temperatures. It is observed that the peak frequency of oscillation at 300K is 100GHz and the same elevated to 107GHz for an increase of junction temperature upto 600K. The avalanche frequency of oscillation is observed to be 48GHz. Fig-2 shows temperature dependent negative resistivity plots of the active device. The peak resistivity value at 300K is found to be $5\times10^{-2}\Omega$m. The study also reveals that the value of negative resistivity gradually decreases with increasing temperature and at 600K the value reduces to ~ 30%. The profile clearly indicates that the possibility of generation of RF power is more in the mid active region. Fig-3 shows the designed cylindrical FBP. Fig-4 denotes the T-Ray Thermographs of Malignant and Non-Malignant cells in FBP. In case of normal fatty breast tissue the temperature rise, as a result of absorption of T-Ray radiation, is insignificant (almost in between 300K-310K).Whereas the temperature variation and enhancement is quite significant in presence of malignant breast tissues. The corresponding thermographs revels the temperature variation in between 310K-550K. This increase of temperature is due to the presence of more water in cancer affected cell in breast organ. The increase of temperature is more near the T-Ray radiation source and decreases gradually with distance. The dimension of the malignant tumour has been considered to be less than 1mm. The published literature, dealt with X-Ray radiation, shows that malignant tumour of such a small dimension could not be predicted with such accuracy by simply adopting a cost effective, room temperature and easy technique [5].

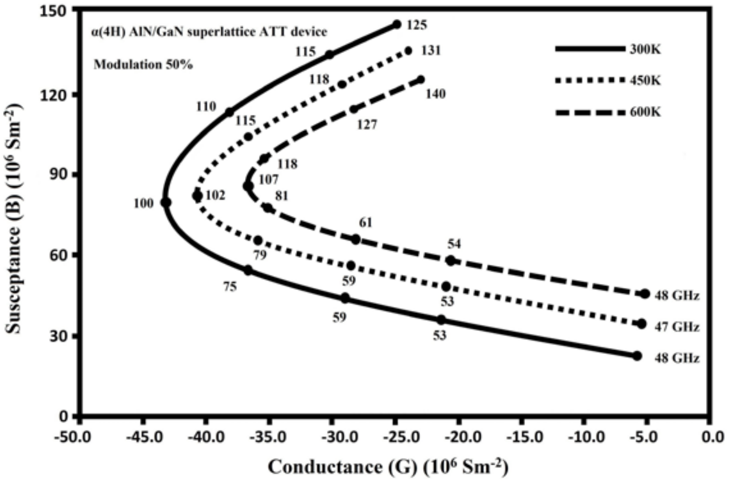


Figure 1 : Temperature dependent admittance plots of Wz-GaN/AlN superlattice ATT device at W-band

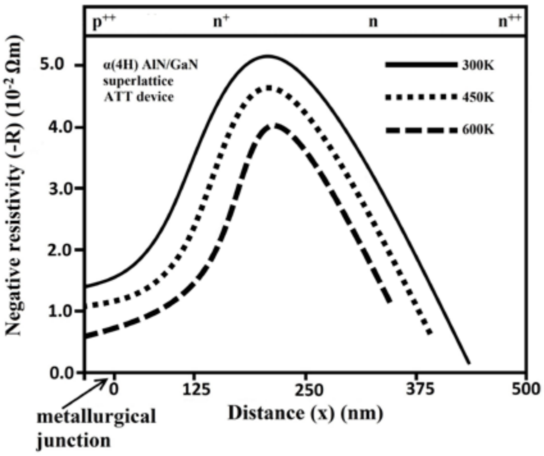


Figure 2 : Temperature dependent negative resistivity plots of Wz-GaN/AlN superlattice ATT device at W-band

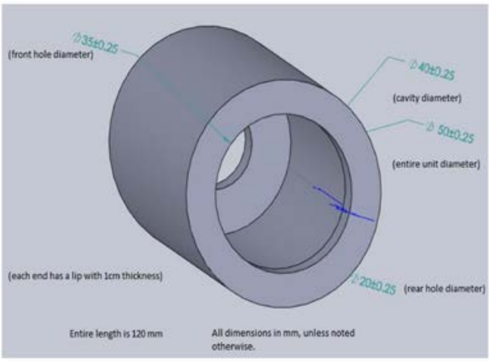
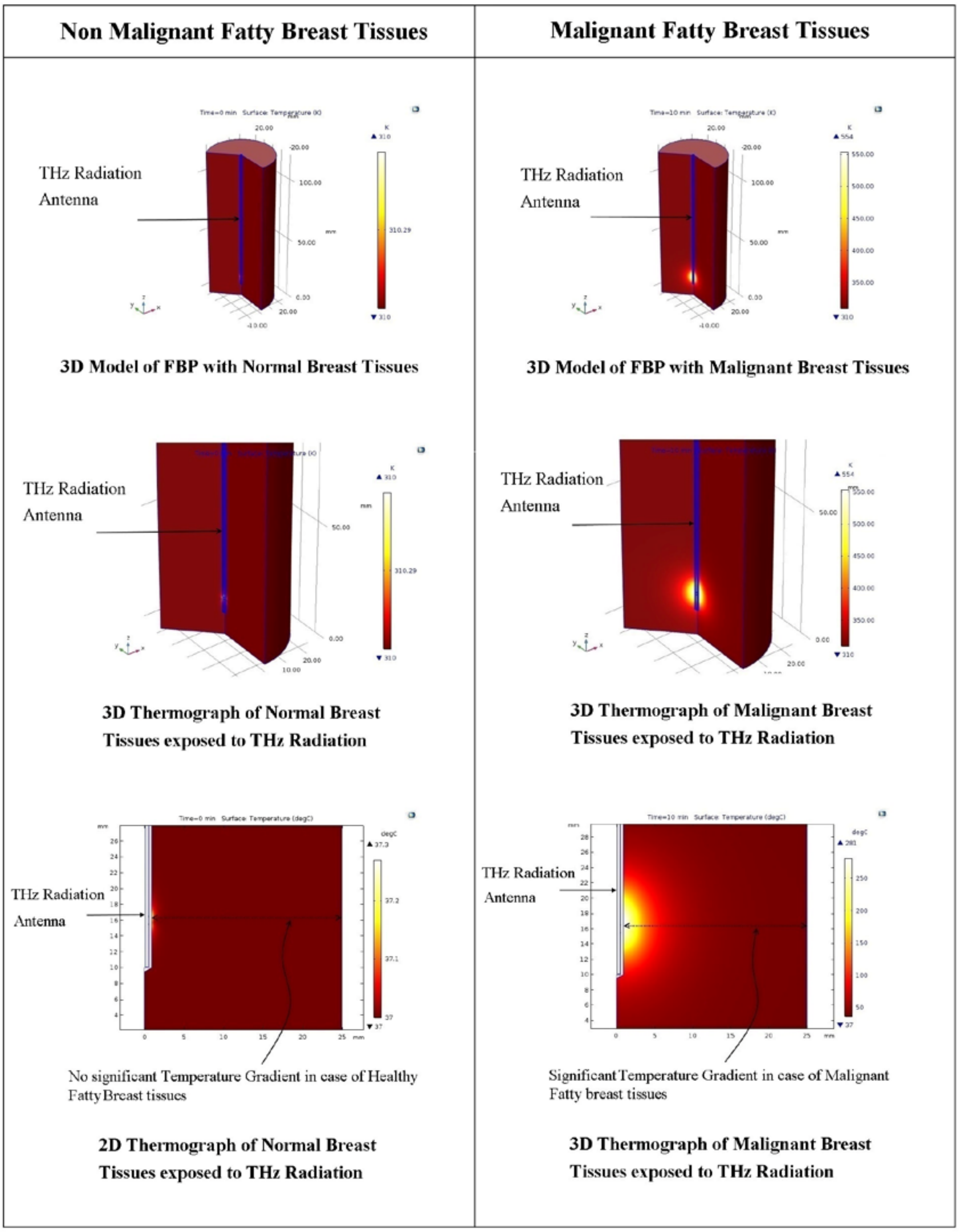


Fig 3: Schametic Diagram of FBP



3D Model of FBP with Normal Breast Tissues

3D Model of FBP with Malignant Breast Tissues

3D Thermograph of Normal Breast Tissues exposed to THz Radiation

3D Thermograph of Malignant Breast Tissues exposed to THz Radiation

2D Thermograph of Normal Breast Tissues exposed to THz Radiation

3D Thermograph of Malignant Breast Tissues exposed to THz Radiation

Fig 4 : Simulation Thermographs: THz Thermal Imaging of Normal & Malignant Breast Tissues

4. Conclusion

A generalized Quantum Modified Non-Linear Drift- Diffusion (QMNLDD) simulator for designing and studying GaN/AlN exotic MITATT device has been developed by the authors. The necessity of incorporation of superlattice properties in conventional model is to improve the high-frequencies electrical and thermal properties of the MITATT Device. GaN/AlN superlattice is found to be a good replacement of conventional GaN flat profile devices as far as improved admittance, electrical field profile, power output and efficiency are concerned. T-Ray Radiation Thermographs clearly establish the accuracy level of T-Ray imaging technique in detecting malignant breast tumour of <1mm diameter. The study, for the first time establishes the superiority of GaN/AlN superlattice based T-Ray Radiation source in hypothermic analysis of breast malignancy when the affected organ is inside a cylindrical FBP. To the best of authors' knowledge this is the first report on superlattice MITATT Device in non-invasive low cost and accurate identification of Breast Cancer.

References

[1] Mukherjee, M., Mazumdar, N., and Roy, S.K., Semiconductor Science and Technology (2007) GaN IMPATT diode: a photo-sensitive high power terahertz source, 22,1258.

[2] Mukherjee, M., Mazumdar, N., and Roy, S.K., IEEE Trans Device and Materials Reliability (2008) Photosensitivity analysis of gallium nitride and silicon carbide terahertz IMPATT oscillators: comparison of theoretical reliability and study on experimental feasibility, 8, 608-620.

[3] Kundu, A., Adhikari, S., Das, A., Ray, M., and Mukherjee, M., Microsystem Technologies (2018) Design and characterisation of asymetrical superlattice Si/4H-SiC pin photo-diode array: a potential opto-sensor for future applications in biomedical domain, DOI 10.1007/s00542-018-4119-4.

[4] NSM Archive, NSM Archive - Physical Properties of Semiconductors, www.ioffe.ru/SVA/NSM/Semicond/

[5] George, T., Rufus, E., Alex, Z.C., ARPN Journal of Engineering and Applied Sciences (2015) Simulation of microwave induced thermo-accoustical imaging technique for cancer detection, 10.