Design and Analysis of Novel Room Temperature T-Ray Source for Biomedical Imaging: Application in Full Body Prosthetics

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1. **Abstract**

The authors have designed and studied the super lattice terahertz device for accurate detection of cancer cell in a Full Body Prosthetic (FBP). For this a generalized non-linear simulator is developed and the same is verified by comparing the results with those of experimental observation. The model predicts that identification of cancerous cell in 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 authors have also studied the effects of modulation on electric field profiles for different phase angles. The simulator incorporates the physical and electrical properties of GaN/AlN super lattice, 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 super lattice 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).

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

2. Introduction:

The terahertz region (1THz= 1012 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 is the uniqueness of T-Ray-imaging in medical applications for providing complimentary information to the existing imaging techniques. For checking the viability of T-Ray imaging for an FBP, a full scale simulator will be developed. The Comsol based model will consider the healthy and malignant cells under various operating conditions inside an FBP, so as to approximate a human body. The simulated Terahertz imaging device will be used to locate the condition and location of the target cells. In addition to being relevant to detecting malignant tumors in a modeled FBP, the findings could further be useful in analysis of customized bioreactors for the biotechnology & pharmaceutical 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 a 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 structure with asymmetrical doping profile in central active region results in spatial separation of mobile electrons & holes within the central region of the designed ATT device. This improves the electrical/electronic/ transport properties such as carrier life-time, saturation velocity and mobility significantly. The band to band transition & drifting of charge carriers in the active region of the device further induces a current-pulse in the external-circuit and this generates an oscillation of desired frequency in THz region. The authors have earlier developed and published a non-linear, self-consistent, large-signal simulator for the realistic modeling and analysis of MITATT devices [1-2]. In the present study, the authors have used that simulator with some important modificationfor the various quantum aspect of carrier transition in asymmetrically doped GaN/AlGaN super-lattice structure. Mixed Quantum Classical Drift Diffusion model is used for solving non-linear Poisson and charge continuity equations subject to appropriate boundary conditions [3].The validity of the model is established by comparing the simulated data with experimental findings.

A huge research work has been done, by this time, with Wide Band Gap (WBG) semiconductor based MITATT/IMPATT devices in current years [1-2]. The research works are mostly focused on IMPATT mode of operation with flat type doping density distribution. The published studies have established the potentiality / superiority of wide-bandgapSiC, III-V GaN and Si/SiC materials for generating T-Ray signal with a medium to low efficiency [1-2]. To the best of authors' knowledge asymmetrically doped super-lattice MITATT devices are not presently available in published literature. High-frequency oscillation generation requires high mobility of charge carrier in transit. Specially designed super-lattice structure is much promising from this aspect of study; this has prompted the authors to choose such exotic doping profiles for designing of a room-temperature and efficient power-source at Terahertz frequency 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 ~ 2x105 m/s, critical breakdown field ~ 2x108 V/m, are expected to be a potential pair for developing a super lattice 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 GaNepilayer [4]. Thus the authors have chosen AlN/GaN super lattice for designing the high power, high frequency ATT device.

Worldwide physicians are concerned for the early diagnosis of cancer in human-body so as to ensure that patient's life could be saved. Most of the non-invasive imaging techniques, those are commonly available now-a-days, mostly rely upon X-Ray. Though X-Ray is an ionizing radiation and it's a secondary cause of malignancy. Moreover, early diagnosis of malignant tumor is the biggest unsolved issue / problem as X-Ray can only detect tumor of dimension > 7 mm. T-Ray, on the other hand, is non-ionizing and thus expected to identify cancerous tumor of less than 1mm diameter. This possibility is thoroughly studied by the authors in the present paper by designing a computer based FBP system with malignant and non malignant cell/ tissues tumors of various dimensions within the designed FBP. COMSOL multi-physics based semiconductor /RF module and heat transfer module are used for this purpose.

3. Methodology:

This part of the research article will deal with the design and simulation methodology, imposed boundary conditions and the device dimension details. The work flow diagram is shown in Fig-1.

A. Quantum Modified Non-Linear Drift-Diffusion (QMNLDD) model for ATT Devices:

The asymmetrically doped AlN/GaN-ATT (p++ -n- - n+ - n++ doping profile) Terahertz source and detector have been designed and analyzed in the paper. The physical properties including thermal/electrical/electronic properties of AlN/GaN materials along the symmetric axis of the device are shown in Table 1. The authors have made a generalized, non-linear Large-signal (L-S) simulation to get original / realistic view of the device characteristics under various operating conditions. For each instant of time, the physical properties, including, electric field, charge carrier current components and 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 different modulation factors at the boundaries of the active region, subject to satisfaction of appropriate boundary conditions. The authors have considered the effect of introducing a buffer n-bump layer of appropriate doping density in between the substrate and epi-layer.

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

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

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

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

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

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

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

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

Where, $G_{A_{n,p}}(x,t)$, $G_{T_{p,n}}(x,t)$ and $G_{ph_{p,n}}(x,t)$ represent the avalanche generation rates and tunnel carrier current generation rates and opto-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 super lattice by means of doping, m_n^* is the effective mass of electron , $\hbar(\frac{h}{2\pi})$ is the normalized Planck's constant, q (1.6×10^{-19} C) is charge of the electron and h (6.625×10^{-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.

B. Simulaion of FBP Model

ComsolMultiphysics 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

C. ComsolThermographic 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].

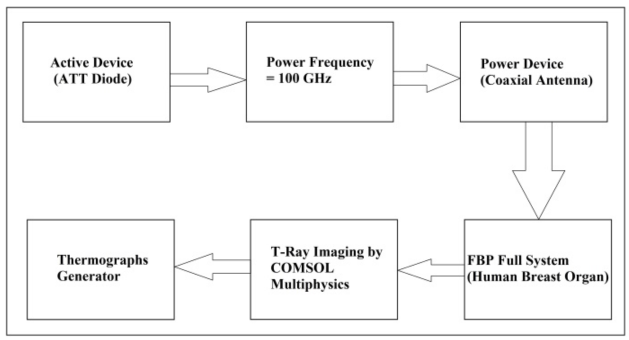

Fig 1 : Work flow diagram of the T-Ray Scanning and Imaging system developed in-Situ

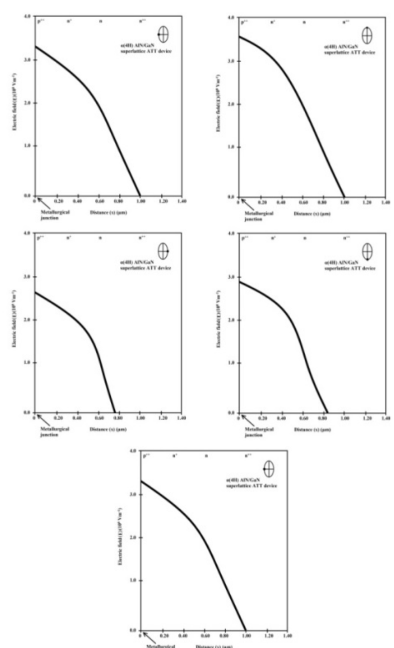

Figure 2 : Electric field properties of Wz-GaN /AlN superlattice ATT device at W-band

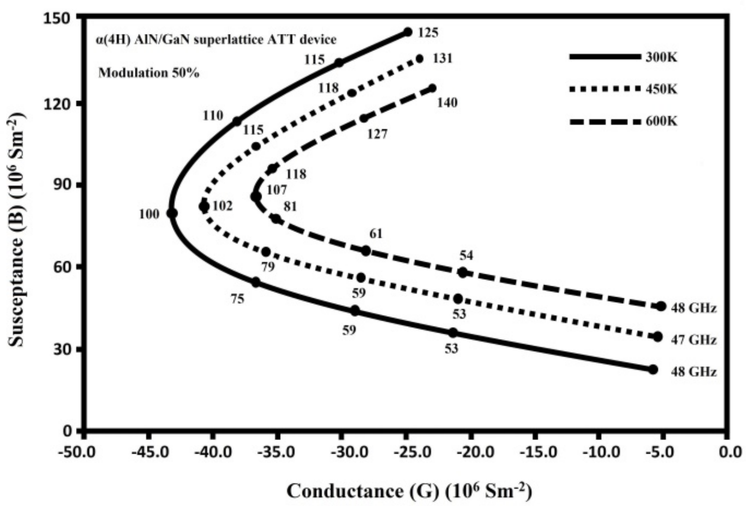

Figure 3 : Temperature dependent admittance plots of Wz-GaN/AlN superlattice ATT device at W-band

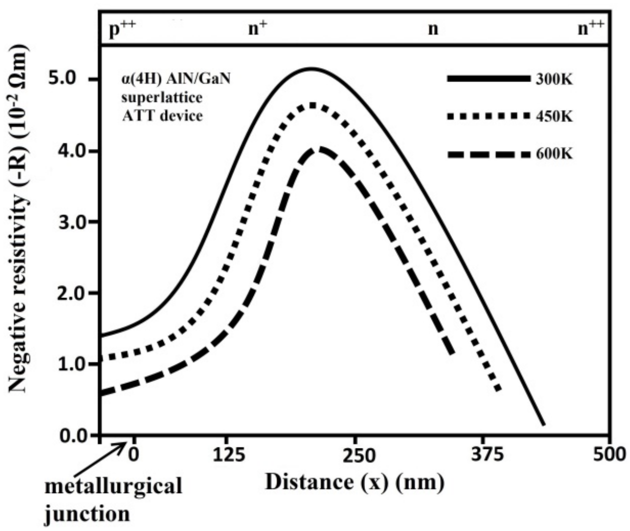

Figure 4 : Temperature dependent negative resistivity plots of Wz-GaN/AlN superlattice ATT device at W-band

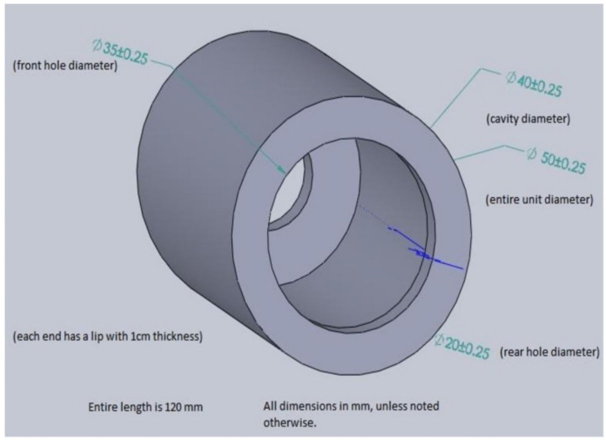

Fig 5: Sehametic Diagram of FBP

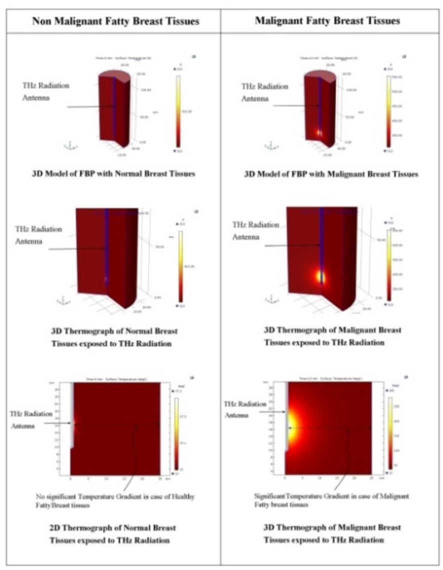

Fig 6 : Simulation Thermographs: THz Thermal Imaging of Normal & Malignant Human Breast Tissues.

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 ($cm^2/V{\cdot}s$)	1500	8500	500 80	1000	1250	300
5	Hole Mobility	μ_p ($cm^2/V{\cdot}s$)	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

4. Result and Discussion:

The electric field snapshots are shown in Fig-2 for different phase angles. It is depicted that the device breaks down at a critical electrical field of $1.1\text{x}10^8$V/m. The active region width ~ 0.8µm. The effects of modulation at different phase angle are shown in the figures. Fig-3 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 a increase of junction temperature up to 600K. The avalanche frequency of oscillation is observed to be 48GHz. Fig-4 shows temperature dependent negative resistivity plots of the active device. The peak resistivity value at 300K is found to be $5\text{x}10^{-2}\Omega$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-5 shows the designed cylindrical FBP. Fig-6 denote 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].

5. Conclusion:

A generalized Mixed 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 super-lattice doping and properties in conventional model is to improve the high-frequency electronic / electrical and thermal properties of the MITATT Device. GaN/AlN asymmetrical super lattice 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 diagnosis of malignant breast tumour of <1mm diameter. The study, for the first time, establishes the superiority of GaN/AlN super lattice based T-Ray Radiation source in hypothermic/thermal analysis of malignancy when the affected organ is inside a designed cylindrical FBP. To the best of authors' knowledge this is the first report on asymmetrical super lattice MITATT/ATT Device in non-invasive low cost and accurate identification of Breast Cancer.

6. References:

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