Design Optimization of a SiC based ATT diode for harmonic mode operation

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Abstract: The paper deals with design and analysis of Si/4H-SiC superlattice based Avalanche Transit time (ATT) device operating at Terahertz frequency region. A generalised non-linear quantum drift diffusion model is developed for the analysis. The authors have studied the higher harmonic effects on the high frequency performances. It is observed that due to the superlattice structure, the device is capable of generating a considerable amount of power (~100 mW) even at 3rd harmonic oscillation. The device is oscillating at fundamental mode of frequency ~ 0.5 THz with an efficiency of ~ 10% The authors have made the analysis realistic by incorporating the temperature dependent carrier ionization rate, saturation drift velocity, mobility and effective mass. To the best of authors' knowledge, this is the first report on higher THz region harmonic analysis of Si/4H-SiC superlattice-ATT device.

1. Introduction

The terahertz (THz) regime (0.1-10 THz) is rich with emerging possibilities in remote sensing, imaging and communications, with unique applications for detecting hidden biological weapons and explosives. Since the last decade scientists working in this area are showing significant interest to develop solid state sources that may generate THz power. Among all two-terminal semiconductor devices (Gunn, IMPATT, TRAPATT, BARITT etc.), IMPATT devices have already emerged as the most efficient solid state sources that can deliver highest RF power even at 300 GHz [1]. Although the conventional IMPATT diodes fabricated on GaAs (Gallium Arsenide) and Si (Silicon) are found to be reliable, these are limited by power and operating frequencies due to the fundamental limitations of the material parameters. On the other hand, wide band gap semiconductor like SiC (Silicon Carbide) and compounds based on it have excellent material properties that can be explored to develop high power and high frequency IMPATT devices. The authors have therefore designed IMPATT diode based on superlattice Si/SiC, since this material pair offers (i) 10 times higher Ec, and (ii) 2 times higher vs in comparison to those of Si and GaAs . Si/SiC superlattice has an energy band gap of 3.4 eV at room temperature. This high value of the energy band gap in the superlattice enables the devices based on this material pair to support peak

internal electric field (EC) about ten times higher than Si and GaAs. The fabrication of ATT device at Terahertz region is complex and costly. Though the authors have earlier attempted for the fabrication of such devices, but due to the narrowing of avalanche region / drift region, the fabrication becomes a complex phenomenon. The authors in this paper have addressed the issue by introducing harmonic effects on the high frequency performance of the device. The device is operating at 0.5 THz at fundamental mode of operation. However, by tuning the circuit, the device could be operated even at > 1.0 THz with a moderate to higher power output. The authors have developed a self consistent; quasi-2D non-linear, voltage –driven Large Signal (L-S) simulator for designing superlattice Avalanche Transit Time (ATT) device. The simulator incorporates the effects of inter-sub-band tunneling, hot carrier effect, quantum size effect, realistic field and temperature dependent carrier density, mobility in superlattice active region. Also the saturation velocity as a function of reverse bias field has been incorporated in the present analysis. To the best of authors' knowledge this is the first ever report on harmonic effects in super-lattice THz-IMPATT.

2. Methodology

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

2.1 Quantum Modified Classical Drift-Diffusion (QMCLDD) model

Large signal analysis of IMPATT diodes is an essential prerequisite for perfect design and implementation of THz oscillators. The generalization, accuracy and efficiency of the study have become very popular through the decades [1-7]. Numerical solutions are preferred over analytical modelling of large signal performance, since tremendous non-linear processing occur within this device structure. Present study of complete analysis involves generalised & non-linear simulation of DDR type (p+pnn+) heterostructure IMPATT device, excluded from any abrupt assumption. This, heterostructure is mainly developed by Si/ 4HSiC.

The present model is based upon self consistent single harmonic analysis of IMPATT device, where the slightly changed "field-maximum method"[8] is assigned for producing detail analysis of Electric field profile in snap-shot mode, carrier current density depending upon the width of active region for a full cycle of oscillation. The non-linear model, associated in this program, comprises of differential equations describing particle concentrations, equations highlighting current density, ionization rates of the carrier which are field-dependent & many other effects including depletion charges etc. The drift velocity of charge-carriers within a specific range of temperature is also considered.

A Quantum Corrected Drift Diffusion (QCDD) model is employed for high modulation analysis. An electric field following a sinusoidal variation of the form $\xi = \xi_0 + m_i \xi_0 \sin\omega t$, where ξ_0 is the time-invariant maximum field value and m_i is modulation index. The modulation index is changed to obtain large signal effect of IMPATT diode.
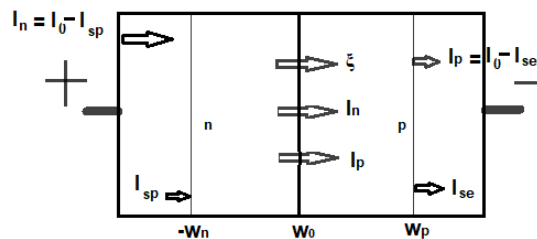

Figure1. Hetero-structure p-n junction ATT diode active region under reverse bias operation

The heterostructure Si/4HSiC IMPATT simulation effects are presented here, where transport mechanism within the mesa structure is considered to be directed along the symmetry axis. The equivalent circuit is shown in Figure 1. Instantaneous electric field profile in the course of oscillation is a keynote of the analysis. A precise & effective single harmonic model [9] is analysed to develop impedance & admittance characteristics of the device depending upon signal amplitude in THz frequency range. As depicted in Figure 2, the mode of biasing is DC which is coupled to an AC supply within a finite extent, so that, mathematically it is expressed as $\phi_t = \phi_{dc} + \phi_{rf} \sin(\omega t + \psi)$, '$\omega$' being the operating frequency & 'ψ' is the beginning phase angle. Complete current of the diode therefore including both DC & AC components, is given by:
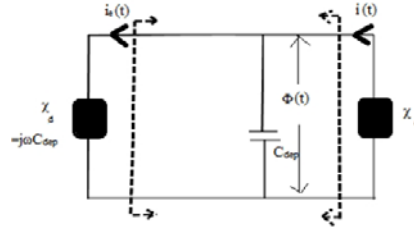

Figure 2. Display of peripheral current and voltage of IMPATT diode, C_{dep} = depletion region capacitance, χ_d = diode admittance, χ_c = circuit admittance

$$i_{total}(t) = -(C_{dep})\frac{d\phi_t}{dt} + i_e(t) \tag{1}$$

The expression for diode admittance χ_d, depending on the oscillation frequency ω is given by

$$\chi_d = j\omega C_{dep} + j\omega C_{dep}\alpha_0 i_{rf}\, e^{-j\left(\frac{\omega\tau_{dep}}{2}\right)}\left\{\alpha_0{}^2 - \frac{\alpha_0{}^2 \sin\left(\frac{\omega\tau_{dep}}{2}\right)}{\left(\frac{\omega\tau_{dep}}{2}\right)}e^{-j\left(\frac{\omega\tau_{dep}}{2}\right)} - 2i_{dc}\left(\omega^2/\omega_\alpha^2\right)\frac{\{1+(1-\frac{\alpha_0{}^2}{i_{dc}})^{\frac{1}{2}}\}}{i_{dc}}\right\} \tag{2}$$

Where α_0 is a constant and ω_α is the avalanche frequency.

The simulation is conducted over large space & changing the meshes. For operating frequency at maximum values, the output power is obtained using the expression,

$$P_{rf} = (\Phi_{rf})^2 \cdot |-G_p| \cdot \left(\frac{\alpha_r}{2}\right) \tag{3}$$

Here G_p is the conductance (negative) at the top frequency.

3. Results and Discussions

The structural modeling of Si/ 4HSiC double drift hetero-structure at 0.5THz has been optimized & displayed in Table: 1. The modeling is based upon Punch through of electric field profile & optimization is carried out in the successive way[11,12]. It is found that for moderately high punch through diode(MHPTD) with doping concentration for p-side, about 16×10^{23} /m³ & n-side, about 18×10^{23} /m³ the time invariant breakdown voltage appears to be 100V with a fixed current density 6×10^9 A/m².

The peak electric field is obtained at the phase angle 90^0, as expected, having the magnitude 5×10^8 V/m. The high modulation admittance profile shown in figure 3 for MHPTD structure shows that the maximum negative conductance decreases from -238×10^6 S/m² at 0.5THz to -150×10^6 S/m² with voltage modulation increases from 5% to 50%. Figure 4 shows that harmonic variation at 5% & 50% voltage modulation for Si/ 4HSiC heterostructure double drift region IMPATT diode where the 2nd & 3rd harmonic values respectively at 1.18THz & 1.65THz are obtained with

gradually decreasing highest negative conductance values which match well with the validity of large-signal synthesis of the device. Figure 5 shows the variation of high frequency power & efficiency output with percentage modulation where it is seen that the output power attains the maximum value of 297 x 10^9 W/m^2 with 50% maximum efficiency for MHPTD structure at 0.5THz, where both decrease with increasing frequency.

Table: 1 Structural modelling parameters of super-lattice (Si/4H SiC) IMPATT in MHPTD model for high modulation analysis at 0.5 THz

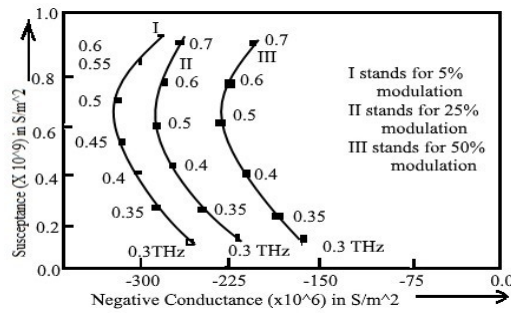| Parameter	Value
Peak Conductance($-G_p$ x 10^6)	-238
Peak Susceptance($-B_p$ x 10^6)	600
Negative resistance(in Ω)	6.0
p-side depletion layer width(in nm)	120
n-side depletion layer width(in nm)	114
Bias current density(A/m^2)	6 x 10^9

Figure 3: Admittance plots of Si/SiC superlattice IMPATT at fundamental mode of oscillation
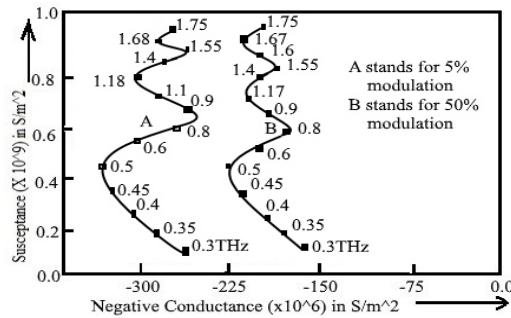

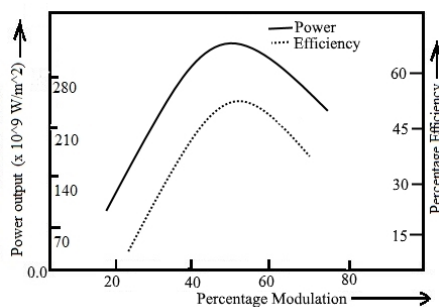Figure 4: Higher harmonics on admittance plots of Si/SiC ATT device for different voltage modulation

Figure 5: Power-output and efficiency variation with percentage modulation

4. Conclusion

The authors have studied and reported the large signal modeling of Si/SiC super-lattice ATT device incorporating the higher harmonic effects. The generalized simulation technique, incorporating physics as much as possible, is developed by the authors. Effect of higher harmonic on THz admittance plots is studied and it is found that due to the super-lattice structure harmonic effects are considerably good in Si/SiC devices. To the best of the author's knowledge this is the first report on hetero-structure IMPATT at this frequency level with the proposed super-lattice Si/4H-SiC.

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