OPTICAL-MICROWAVE EFFECTS IN IMPATT DIODE OSCILLATORS*

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Abstract

Significant difference in optical-microwave interactions, in Si IMPATT oscillators, due to electron and hole initiated avalanches have been demonstrated using ring device structures and modified disc and post type waveguide cavity. A large signal model accounting for this difference gives a good agreement with the experimental results.

Introduction

The sensitivity of IMPATT oscillator power output and frequency to the effective leakage current of the device has been proposed for possible direct optical modulation and phase locking.(1) Recently it has been experimentally demonstrated(2) that not only the magnitude of leakage current is important in determining the extent of the microwave-optical interaction, but its composition in terms of electron and hole currents must be considered whenever electron and hole ionization rates are unequal. The purpose of this paper is to present an analytical treatment of the IMPATT oscillator that takes into consideration the composition of leakage current, thereby developing a large signal model which gives good agreement between theory and our experimental results.

Experimental Setup

The experimental set up requires a device structure, an optical source and a microwave cavity which allows the photogeneration of carriers while the device is in RF operation. We have used He-Ne laser (6328A°) which has an absorption length of about 3μ in Si. In order to change the relative composition of the leakage current in the flat profile p^+-n-n^+ Si IMPATTs, the diode was illuminated from p^+ contact to generate electron dominated photocurrent and from n^+ contact to generate hole dominated photocurrent. The two structures shown in Fig. 1 were fabricated from the same wafer, one with junction side up or Top Mounted (TM) and the other with junction side down, i.e. Plated Heat Sink or Flip Chip (FC). The diodes have an active layer thickness of 3.6μ and doping concentration of 7.5×10^{15} cm^{-3} with a resultant breakdown voltage of about 70V. Salient features of the device structure, various design trade-off involved in device fabrication, and evaluation of possible spreading resistance and other two dimensional effects induced in the active region of the device by the ring contact have been reported elsewhere(2,3) which demonstrates that the device structure does not inhibit RF performance.

A disc and post type waveguide cavity has been constructed to allow a direct optical path from the laser to the optical window during RF operation of the diode. Because of the expected high thermal resistance of the TM devices both FC and TM devices were pulse operated (0.2 μsec pulse duration, 400 pps) in the modified cavity with identical tuning discs and different sliding short positions (to compensate for different junction capacitance).

The photocurrent was generated by focussing a 2.5 mw He-Ne laser onto the 0.1 mm diameter optical window and was varied by using various filters. Photocurrent of approximately 0.5 mA were generated in both FC and TM devices at maximum laser output, both structures exhibit similar quantum efficiency.

Large Signal Model

The IMPATT model is an extension of large signal model described previously,(4) but the restriction of equal ionization rates and drift velocities of the carrier has been removed. The diode is approximated by a one-sided Read Structure, with the avalanche region being analyzed following the treatment by Lee et. al.[5] The avalanche particle current density for sinusoidal field perturbation of frequency ω is given by

$$I(t) = M_1 I_s \exp(-2V_1 \cos \omega t) \sum_{k=0}^{\infty} \frac{2-\delta_{ok}}{1+k^2\Theta^2} (\cos k\omega t + k\Theta \sin k\omega t) I_k(2V_1) \qquad (1)$$

Where I_s=saturation current, I_k=Modified Bessel Function of order k, δ_{ok}=Kronicker delta function, $\Theta=M_1\omega\tau$, V_1=normalized avalanche voltage across the avalanche region M_1=effective DC multiplication and τ_1=response time and is given by

$$\tau_1=\tau_{in}\{(1-k)+k.\exp(-\int_0^{x_A}(\alpha-\beta)dx)\}^{-1} \qquad (2)$$

where τ_{in}=response time when avalanche is initiated by electrons, k=injection ratio i.e. ratio of hole component of photocurrent to the total photocurrent, α,β= ionization rates for electrons and holes and x_A is the avalanche region width .

Proceeding in a manner analogous to [4], a complete steady state circuit model for operation of an IMPATT oscillator at an angular frequency ω is obtained and is shown in Fig. 2(a). For reasonable values of normalized avalanche voltage and photocurrent much smaller than the constant DC bias current, the strength of various current generators in Fig. 2(a) is expressed by the following relations:

$$I_{dc} = I_s M_1 I_o^2(2V_1) \qquad (3)$$

$$i_1 = 2\beta I_{dc} \sin\phi \cos\phi[1-\frac{I_2(2V_1)}{I_o(2V_1)}] \qquad (4)$$

$$i_2 = 2\beta I_{dc}\cos^2\phi[1-\frac{I_2(2V_1)}{I_0(2V_1)}\tan^2\phi] \qquad (5)$$

$$i_3 = 2\beta I_{dc} \cos\phi \frac{\sin \Theta_{D/2}}{\Theta_{D/2}} \sin(\frac{\Theta_D}{2}-\phi) [1+\tan\phi \frac{I_2(2V_1)}{I_0(2V_1)} \frac{\cos(\frac{\Theta_D}{2}+\phi)}{\sin(\frac{\Theta_D}{2}-\phi)}] \qquad (6)$$

$$i_4 = 2\beta I_{dc} \cos\phi \frac{\sin \Theta_{D/2}}{\Theta_{D/2}} \cos(\frac{\Theta_D}{2}-\phi)[1-\tan\phi\frac{I_2(2V_1)}{I_0(2V_1)} \frac{\sin(\frac{\Theta_D}{2}+\phi)}{\cos(\frac{\Theta_D}{2}-\phi)}] \qquad (7)$$

$$\cot\phi = M_1\omega\tau_1 \qquad (8)$$

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where $\beta = I_1(2V_1)/I_o(2V_1)$, $\Theta_D = \omega\tau_d$ and τ_d is the transit time through the drift region.

Since displacement current through the junction capacitance is much greater than the reactive currents produced by avalanche dynamics, the model of Fig. 2(a) can further be simplified to the model shown on the left side of A-B in Fig. 2(b), while right side of A-B represents the total series resistance R_s and load impedance $Z_L = R_L + j\ X_L$.

It is to be noted that the current generator i_3 represents the active properties of the diode and its strength is affected by the magnitude and the composition of leakage current through angle ϕ which in turn is related to response time τ_1 by eq. 8. Response time τ_1 can be evaluated using eq. 2 once the injection ratio is known. With the knowledge of the absorption coefficient of light in Si, diffusion length in p and n regions and surface recombination velocity, the injection ratio in the TM and FC devices reported here is calculated to be 0.5 and .98 respectively. Thus photocurrent in TM devices is electron dominated while in FC devices hole current dominates.

Experimental and Theoretical Results

The diode is biased with a constant current source and the oscillator power output and frequency are measured as a function of bias, with photocurrent as a parameter. These oscillator characteristics for a FC device and a TM device are shown in Figs. 3 and 4 respectively. For the TM device, the power is reduced by 20% at a photocurrent to biased ratio of about .0006, while for the FC device this ratio is an order of magnitude higher or .006 (power at maximum bias current is reduced from 250 mW to 200 mW at about 50 μA and 500 μA respectively). The increase in frequency of oscillations is also similar (≃ 10 MHz) at a factor of 10 difference in photocurrent (9.98 to 9.89 GHz and 10.855 to 10.865 GHz for TM and FC respectively). The 1 GHz difference in oscillator frequency is attributed to its sensitivity to the diode junction capacitance.

In order to calculate the power output as a function of bias current with photocurrent as parameter, the diode model of Fig. 2(b) has been used. Once the microwave circuit impedance is known, diode performance for a given diode structure and operating conditions can be predicted using this model. The diode RF power output characteristics without photocurrent are used to determine the RF circuit impedance and subsequently predict the diode performance with photocurrent. Use of such a procedure has been previously described[4], although modified here by a different expression for the response time.

Other important parameters in the model is response time τ_1, which accounts for the composition of photocurrent. As mentioned earlier that the injection ratios for TM and FC devices are 0.5 and .98 respectively and corresponding response times, for the electric field profile at breakdown, are 3.5 psec and 24 psec respectively.

The theoretical results, obtained using the above parameters and shown in Fig. 3 by dotted curve, are in good agreement with the experimental results. At higher bias currents, where power tends to saturate appreciably, the agreement is not that good. This is not unexpected as other saturation mechanisms have not been incorporated in the model.

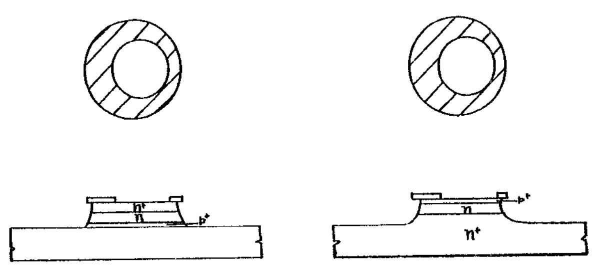
The difference in electron and hole initiated avalanche is also observed in the DC I-V characteristics for FC and TM devices, as shown in Fig. 5. Without photocurrent both the diodes have hard breakdown characteristics, and the photocurrent below half the breakdown voltage is nearly constant. Above half the breakdown voltage the difference in electron and hole initiated avalanches is reflected in the sharper rise in current in Fig. 5(a) for TM device compared to the current in Fig. 5(b) for FC device.

Summary

We have shown that the microwave-optical interaction in IMPATT oscillators is strongly dependent on the composition of the photocurrent. This dependence has been taken into account in the oscillator model which gives a good agreement with the experimental results. This inherent difference in hole and electron initiated avalanches is important in evaluating the effect of reverse saturation current as a power limiting factor in IMPATT oscillators and in determining the optical power requirement for direct optical modulation.

References

1. Vyas, H. P., et.al., "Leakage Current Enhancement in IMPATT Oscillator by Photoexcitation", Elect. Lett., Vol. 13, pp. 189-190 (1977).
2. Vyas, H. P., et.al., "The Effect of Hole versus Electron Photocurrent on Microwave-Optical Interaction in IMPATT Oscillators", IEEE Trans. ED-26, March (1979).
3. Schweighart, A., et.al., "Avalanche Diode Structure Suitable for Microwave-Optical Interaction", Solid State Electronics, Vol. 21, pp. 1119-1121 (1978).
4. Cottrell, P. E., et.al., "IMPATT Oscillators with Enhanced Leakage Current", Solid State Electronics, Vol. 18, pp. 1-12, (1975).
5. Lee, C. A., et.al., "Time Dependence of Avalanche Processes in Silicon", J. Appl. Phys., Vol. 38, pp. 2787-2796, (1967).



(a) FLIP CHIP (FC) (b) TOP MOUNTED (TM)

Figure 1 IMPATT Diode Structures with Ring Contacts

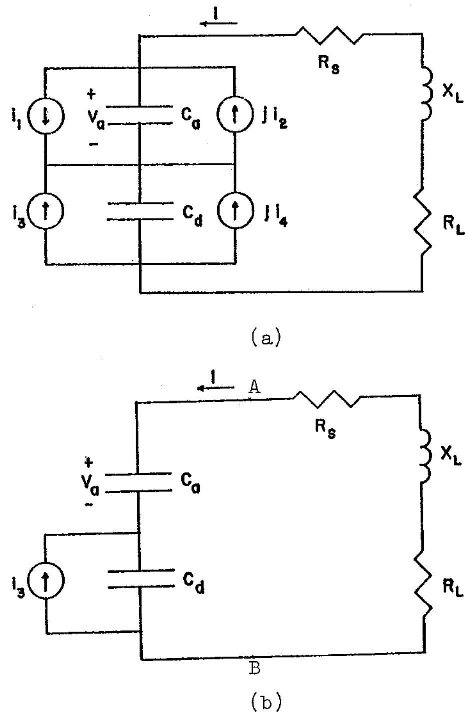


Figure 2 IMPATT Diode Models

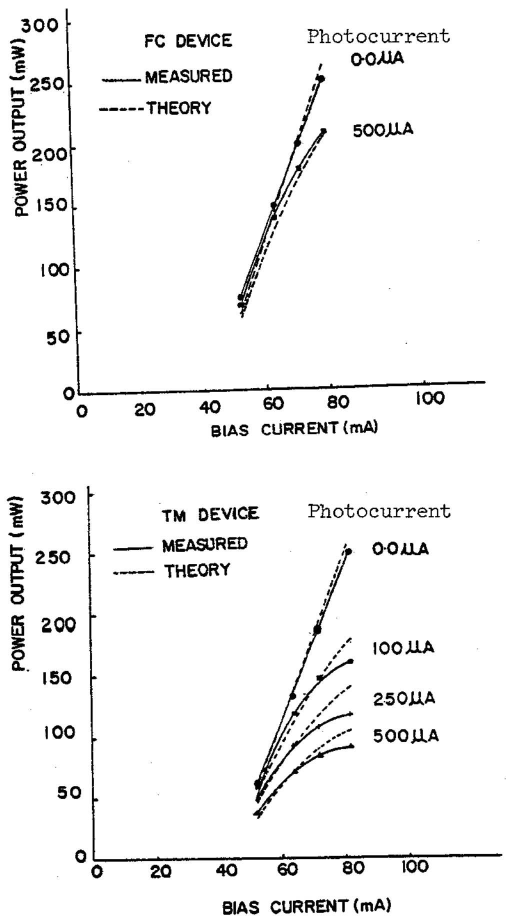


Figure 3 Power Dependence upon Photocurrent

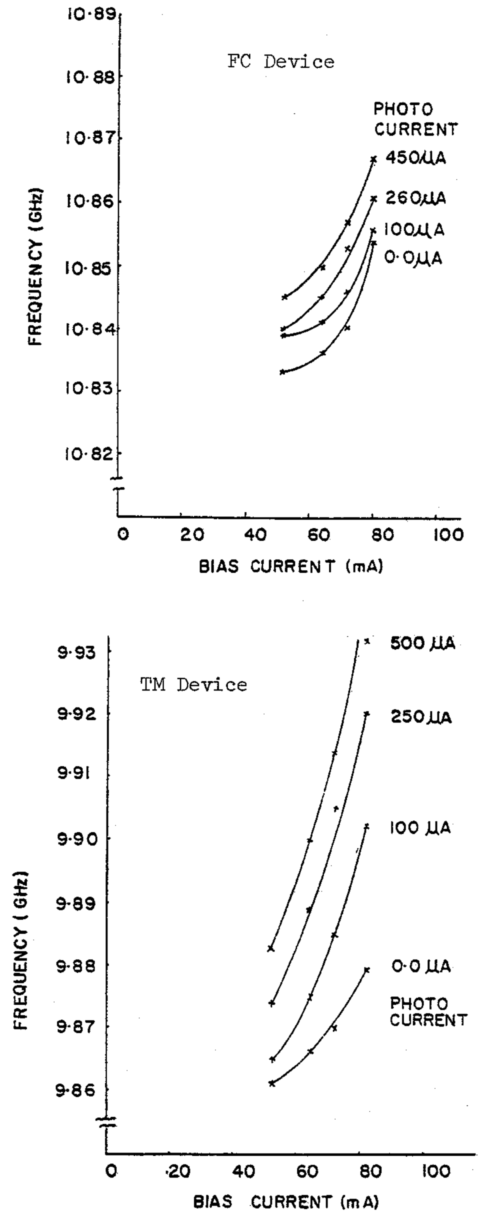


Figure 4 Frequency Dependence upon Photocurrent

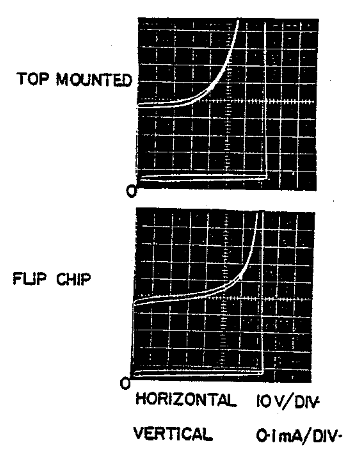


Figure 5 I-V Characteristic of IMPATT Diodes with and without Photocurrent