PERFORMANCE OF AVALANCHE DIODE OSCILLATORS WITH LARGE LEAKAGE CURRENT

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Abstract

Experimental results of the RF performance of 500 milliwatt cw, X-band IMPATT diode oscillators and 30 watt pulsed, S-band TRAPATT diode oscillators with large leakage current are presented. The leakage current was varied from 10 microamps to 10 milliamps by varying the dose rate of high energy electrons from a linear accelerator. Correlation obtained with device models indicate that the principal effects of leakage current on avalanche diode oscillator characteristics have been properly identified.

Introduction

An evaluation of the effect of large leakage current on the performance of avalanche diode oscillators can be important in many applications. It has been shown experimentally that thermally generated leakage current can quench the avalanche in an avalanching diode and lead to thermal instabilities at elevated temperatures. At lower values of leakage current the reduction in RF power of a Read IMPATT diode has been calculated by Misawa[1] using a computer simulation, and the sensitivity of a TRAPATT diode to leakage current has been emphasized by DeLoach and Scharfetter.[2]

In this work the effect of large leakage current on the RF performance of commercially available 500 mW cw, X-band IMPATT diodes and 30 W pulsed, S-band TRAPATT diodes has been measured. The leakage current was varied from 10 microamps to 10 milliamps by varying the dose rate of 100 nanosecond pulses of 10 MeV electrons from a linear accelerator. Calculations of oscillator performance agree well with measured results, indicating that the principal effects of leakage current have been properly identified with the device models developed. In this paper the experimental results and large leakage avalanche diode models are described.

Experimental Results

The X-band IMPATT diodes were tested in a nominal Q, disc and post type waveguide cavity while the S-band TRAPATT diodes were mounted in a multiple slug coaxial cavity. The test setups used for the IMPATT and TRAPATT diodes are shown in Figures 1 and 2 respectively. With proper shielding, these facilities permitted the RF and bias conditions to be monitored during irradiation, that is during large leakage current operation. The diode cavities (evacuated to prevent air ionization effects), test facilities, and measurement considerations have been well documented previously.[3,4]

In using 10 MeV electrons to quantize the effect of large leakage current on avalanche diodes, the effective leakage current must be related to the more readily measured radiation dose rate, either by direct measurement with the diode reversed biased below the breakdown voltage or by calculation if the effective charge generation volume is known. Agreement to within 25% can be obtained with these two approaches, thereby limiting the accuracy of the RF results presented.

The dependence of RF power on leakage current for typical IMPATT and TRAPATT diodes evaluated in this work is shown in Figure 3. The gradual decrease in RF power with increasing leakage current was typical in all silicon and GaAs IMPATT's tested. A bias current of 70 milliamps was used for the IMPATT diode shown, and the power output without enhanced leakage current was 400 milliwatts. In comparison, the rapid decrease in RF power was typical for all the TRAPATT's tested. A pulse bias current of 2.3 amps was used for the TRAPATT result shown and the pulse power output without enhanced leakage current was 25 watts. The IMPATT diode RF power is reduced to 50% of its low leakage value at a leakage to bias current ratio (defined as the critical ratio) of .01, while with the TRAPATT diode this ratio is $4. \times 10^{-4}$. The IMPATT result is in agreement with predictions by Misawa[1], but the TRAPATT measurements are in disagreement with the results of Wierich[5] where critical leakage to bias current ratios of 10^{-6} were predicted. Both predictions were obtained with computer simulations.

Large Leakage Avalanche Diode Modeling

A large signal equivalent circuit of an IMPATT diode including the effects of leakage current was developed by extending the large signal equivalent circuit of Mouthaan[6] without considering leakage. A comparison of the simplified single frequency equivalent circuits is shown in Fig. 4. In these equivalent circuits, I represents the bias current, θ the transit angle through the drift region, C_d the capacitance of the drift region, C_a the capacitance of the avalanche region, R_s the diode series resistance and β a parameter which takes into account large signal effects. β is a function of the voltage V_{a1} across the avalanche region. If a normalized voltage v is defined as $v = \alpha' V_{a1}/\omega \tau_a$ (where α' is the derivative of the ionization coefficient with respect to the electrical field, ω is the frequency of operation and τ_a is the transit time through the avalanche region), then β is given by $I_1(2v)/I_o(2v)$ where I_o and I_1 are the modified Bessel functions of the first kind and of order zero and one, respectively. In our model, we include the effects of leakage current by introducing another angle ϕ determined by $\cot \phi = M\omega \tau_a/2$, where the multiplication factor M is a function of the leakage current I_s and is determined by the relation $I = I_s M I_o^2 (2v)$. The angle ϕ represents the reduction in the 90^o phase lag (between the avalanche current and the voltage across the avalanche region) introduced by the leakage current. That is, the leakage current leads to a premature build up of the avalanche current which deteriorates the optimum phase relationship between current and voltage. If the leakage current approaches zero, then the multiplication factor M approaches infinity and the angle ϕ reduces to zero. A detailed treatment of this model is being published.[7] Using the model, we have obtained excellent correlation between experimental results and theoretical calculations of the RF power dependence upon leakage current, as indicated in Figures 5 and 6 for silicon and GaAs IMPATT diodes respectively.

In addition, we have developed a first order model of TRAPATT operation that permits calculation of the RF power during large leakage operation. This TRAPATT model combines the circuit model of Evans[8] with the device equations of DeLoach and Scharfetter[2]. The oscillator circuit and the assumed diode voltage and conduction current waveforms are depicted in Figure 7. The integral of the conduction current (namely

$I_1 \tau_1 + I_2 \tau_p$) is the total charge generated during the charging period. The dependence of this charge (Q) on the leakage current of the diode can be calculated using the following equation:

$$Q = \frac{W\, I_o}{2\, v_s} \left[\ln \frac{I_o}{I_s} + \ln \left(\ln \frac{I_o}{I_s} \right) \right]$$

where I_s is the leakage current, I_o the avalanche shock front driving current, W the width of the plasma region and v_s the carrier saturation velocity. This equation for total mobile charge can be obtained from equations (27) and (37) in DeLoach and Scharfetter. Knowing the dependence of generated charge upon leakage current, the RF power at the fundamental frequency can be calculated as described by Evans. In this analysis the principal effect of the leakage current is a reduction in mobile charge (Q) generated during the charging period. This reduces the time required to remove the trapped plasma (τ_p) and the time necessary for recovery of the diode voltage (τ_R).

A comparison of the results of this model with experimental measurements of the RF power during large leakage operation is shown in Fig. 8. Although the calculated RF power does not decrease as rapidly with leakage current as the measurements indicate, a principal effect of enhanced leakage has been incorporated in this first order TRAPATT model. However, it should be noted that computer simulations indicate that the recovery cycle may have a dominant effect on the rapid decrease in TRAPATT power at the critical leakage current.(9)

Conclusions

In conclusion, by using the pulses of high energy electrons we have measured the effect of leakage current on the RF power of avalanche diode oscillators. Moreover we have described IMPATT and TRAPATT oscillator models that agree well with the RF power dependence upon leakage current (particularly in the IMPATT mode), indicating that principal effects of large leakage current have been properly identified. Additional work is needed to explain the rapid decrease in TRAPATT power at the the critical leakage current, and this work is currently in progress.

References

1. T. Misawa, "Saturation Current and Large-Signal Operation of a Read Diode", Solid State Electronics, Vol. 13, 1970, pp. 1363-1368.
2. B. C. DeLoach and D. L. Scharfetter, "Device Physics of TRAPATT Oscillators", IEEE Trans. on Electron Devices, ED-17, 1970, pp. 9-21.
3. J. M. Borrego, R. J. Gutmann, P. E. Cottrell, and S. K. Ghandhi, "Transient Ionizing Radiation Effects on IMPATT Diode Oscillators", IEEE Trans. on Nuclear Science, NS-19, Dec. 1972, pp. 328-334.
4. J. M. Borrego, R. J. Gutmann, H. J. Geipel, and S. K. Ghandhi, "Operation of TRAPATT Oscillators Under Transient Ionizing Radiation Conditions", IEEE Trans. on Nuclear Science, NS-20, Dec. 1973, pp. 144-148.
5. R. L. Wierich, "Computer Simulation of Dependence of TRAPATT Oscillations on Minority Saturation Currents", Electronic Letters, Vol. 7, 1971, pp. 189-191.
6. K. Mouthaan, "Characterization of Nonlinear Interactions in Avalanche Transit-Time Oscillators, Frequency Multipliers and Frequency Dividers", IEEE Trans. on Microwave Theory and Techniques, MTT-18, 1970, pp. 853-862.
7. P. E. Cottrell, J. M. Borrego, and R. J. Gutmann, "IMPATT Oscillators with Enhanced Leakage Current", Solid State Electronics, to be published.
8. W. J. Evans, "Circuits for High-Efficiency Avalanche-Diode Oscillators", IEEE Trans. on Microwave Theory and Techniques, MTT-17, 1969, pp. 1060-1069.
9. Private conversation with S. P. Yu and W. Trantraporn, General Electric Company, Schenectady, N. Y.

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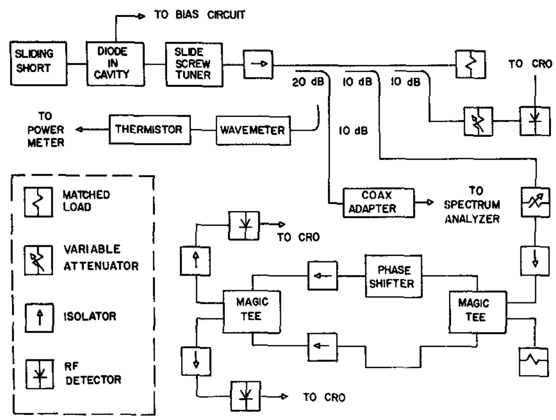


Fig. 1 X-band waveguide IMPATT diode test setup

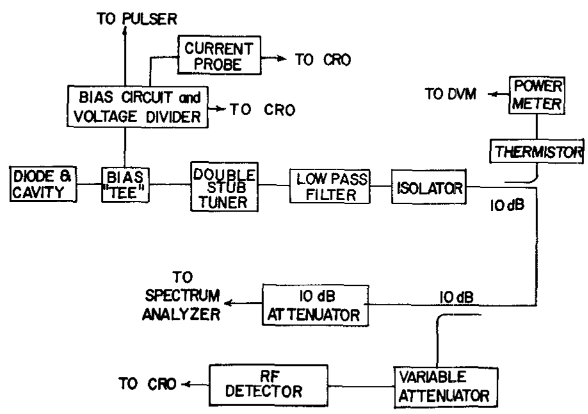


Fig. 2 S-band coaxial TRAPATT diode test setup

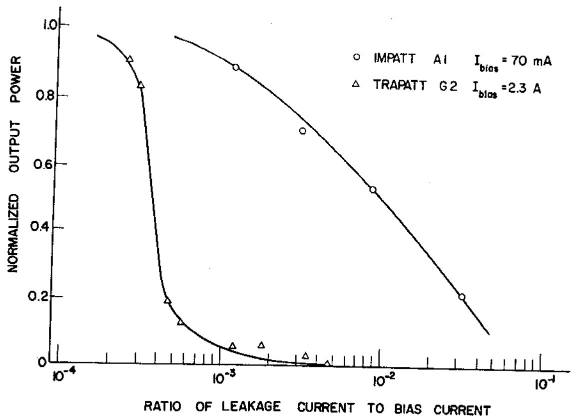
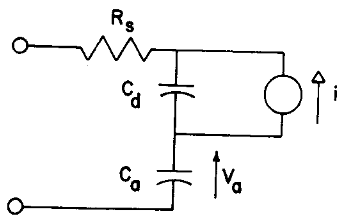


Fig. 3 Compairson of enhanced leakage current on RF power of pulsed S-band TRAPATT and cw X-band IMPATT oscillators



a) NO LEAKAGE CURRENT $\quad i = 2I_\phi \dfrac{\sin^2\frac{\theta}{2}}{\frac{\theta}{2}}$

b) WITH LEAKAGE CURRENT $\quad i = 2I_\phi \cos\phi \dfrac{\sin\frac{\theta}{2}}{\frac{\theta}{2}} \sin\left(\frac{\theta}{2}-\phi\right)$

Fig. 4 IMPATT diode equivalent circuits

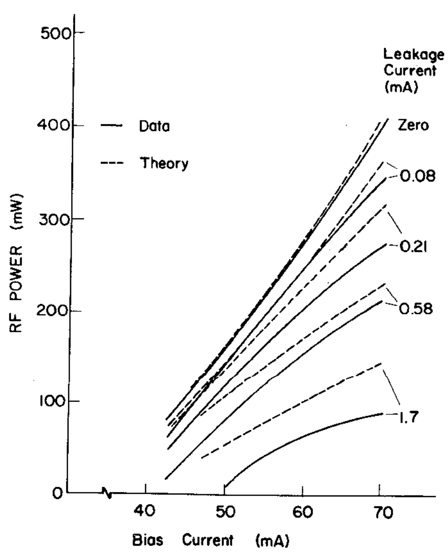


Fig. 5 Comparison of theoretical and experimental silicon IMPATT diode RF power dependence upon leakage current

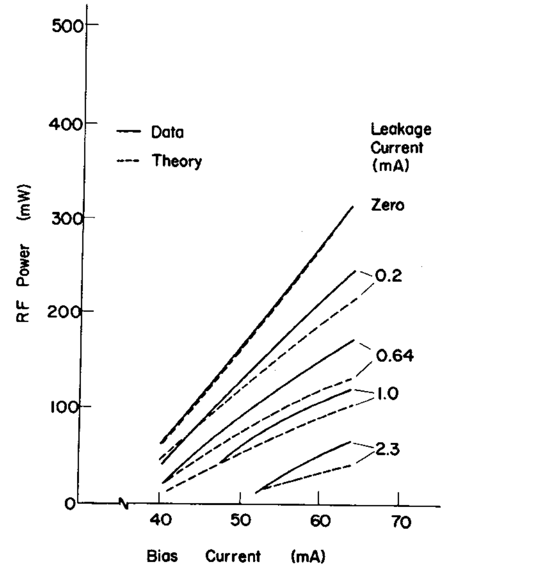


Fig. 6 Comparison of theoretical and experimental GaAs IMPATT diode RF power dependence upon leakage current

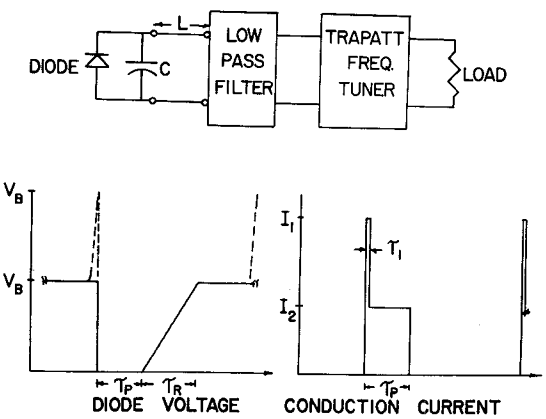


Fig. 7 TRAPATT circuit model with assumed voltage and current waveforms

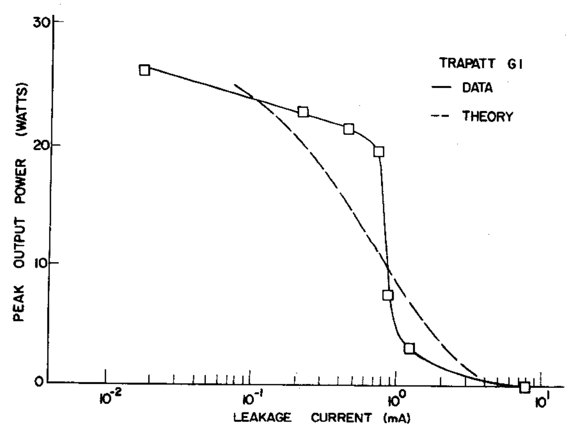


Fig. 8 Comparison of theoretical and experimental TRAPATT diode RF power dependence upon leakage current