

### III. SOLID-STATE MICROWAVE ELECTRONICS\*

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#### A. AVALANCHE DIODE OSCILLATOR

Experimental observations have shown that the output power of an avalanche diode oscillator has a strong dependence on the second-harmonic termination.

The avalanche oscillator diode has been mounted in a package that has separate ports for the fundamental ( $f_0$ ) and second-harmonic ( $2f_0$ ) frequencies. The second-harmonic port was terminated in an adjustable short, and the power output at the fundamental port was observed as the position of the short varied. This resulted in an approximate 3 dB variation in power, as read on an hp power meter with a thermistor mount used. With reference to a matched termination on the second-harmonic port, this represents an improvement of approximately 1 dB, and a degradation of nearly 2 dB. The variation repeated itself every half-guide wavelength at  $2f_0$ , where  $f_0$  is around 8.8 Gc.

The same phenomena observed on the spectrum analyzer showed a much greater variation in power than the 3 dB seen on the power meter. At certain positions of the short (spaced a half-guide wavelength apart), the output at  $f_0$  dropped essentially to zero. Also, the improvement in power was nearly 3 dB relative to that with a matched termination on the second-harmonic port. Qualitatively, the spectrum of the fundamental also improved rather substantially when the short was adjusted for maximum power output.

The discrepancy between the results obtained from the power meter and the spectrum analyzer are mainly due to nonperfect isolation between the fundamental and second-harmonic ports, i. e. , some second-harmonic power is getting out the fundamental port. This additional power will be seen on the meter, but not on the spectrum analyzer.

It should be noted that these measurements were made at relatively low output power for a typical avalanche diode oscillator (only ~5-10 mW), because of poor coupling to the package containing the diode.

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These results seem to indicate consideration of the second-harmonic termination in the design of avalanche diode oscillators with improved efficiency.

D. F. Peterson

#### B. 60-GHz MIXER

A diode mount with reduced height waveguide transitions was designed and built. It will be used to measure the parameters of the Schottky barrier diodes at 60 GHz.

The diodes made during the last quarter have had a 60% failure rate. The failures were traced to back contact failures and poor epoxy bonds in the package. New whisker material and better quality control during assembly should solve the problem.

Noise figure instrumentation has been assembled, and measurements will begin.

J. E. Rudzki

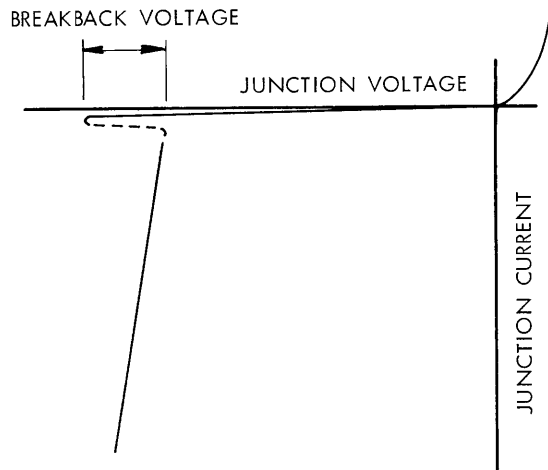
#### C. INVESTIGATION OF SUBTRANSIT-TIME OSCILLATIONS IN THE AVALANCHE REGION OF A P-N JUNCTION

An investigation has been made of the subtransit-time oscillations observed in silicon p-n-n<sup>+</sup> diodes biased into the avalanche region. The doping concentration of the diodes was  $10^{14} \text{ cm}^{-3}$  for the n-region with a width of  $\sim 10$  microns. The p region had a concentration of  $10^{17} \text{ cm}^{-3}$ , and the substrate had a resistivity of  $0.001 \Omega\text{-cm}$ .

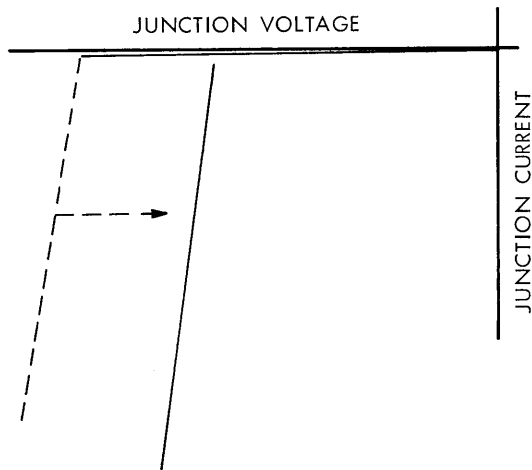
Two types of breakdown mechanisms were considered for the avalanche region. Circuit models were developed for these mechanisms. The behavior of these circuit models in series and parallel resonant circuits was then compared with the behavior of an avalanche diode in similar physical circuits. All calculations were carried out through a nonlinear time domain analysis of the circuits with the aid of the Project Mac computer.

The first type of breakdown considered was a static breakdown. It was assumed that when the diode was biased into the avalanche region that it would follow the static (DC) V-I characteristics. This is similar to the Zener diode curve, except that there exists a breakback in the V-I curve in the avalanche region (see Fig. III-1a). A piecewise linear approximation to this V-I curve was used for the circuit model (see Fig. III-1b and -1c). One modification was made, however, to allow for the transit time of the charge carriers to travel across the junction. This was incorporated into the model by allowing the curve at the onset of breakdown to be in the position of the dotted curve (see Fig. III-1b) and move to its breakback position over a period of 200 psec.

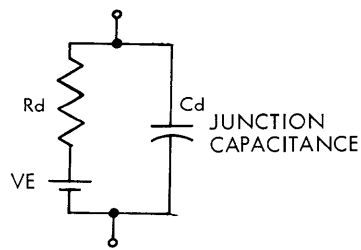
The second type of breakdown mechanism considered was a transient breakdown proposed by P. Penfield. In this model a "bunch" of carriers sweeps across the depletion region of the diode, ionizing as they go, and leaves the junction voltage at a level somewhat lower than its initial value. The junction recovers, however, and does not go into static breakdown. The circuit model for this type of breakdown consists of a battery and



(a)



(b)



(c)

Fig. III-1. (a) Static (DC) V-I curve of avalanche diode in breakdown.  
 (b) Modified piecewise linear approximation to static V-I curve, with transit-time effects included.  
 (c) Circuit model of modified piecewise linear approximation.

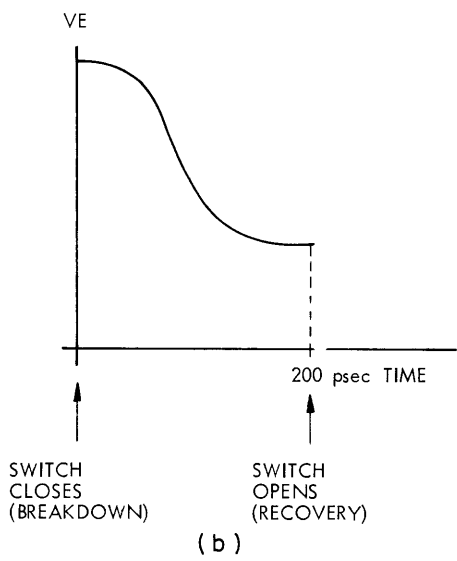
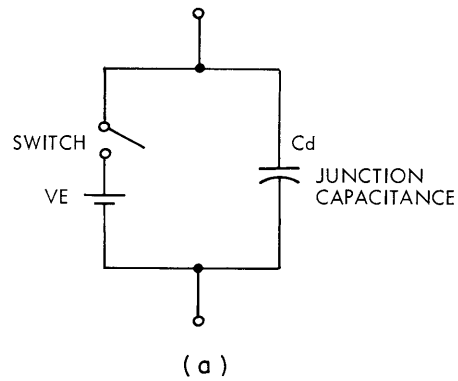


Fig. III-2. (a) Circuit model for transient breakdown mechanism. (b) Voltage,  $V_E$ , as a function of time during breakdown.

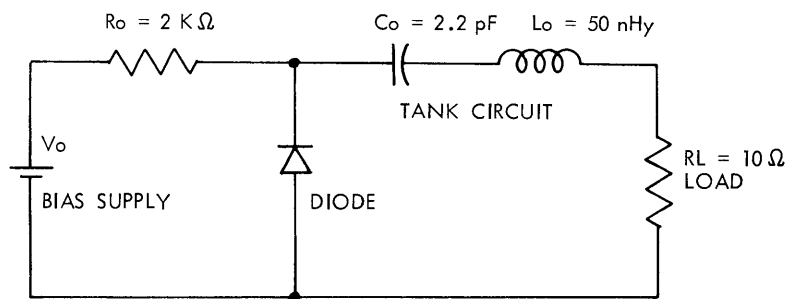


Fig. III-3. Avalanche diode in a series resonant circuit.

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a switch (see Fig. III-2). At the onset of breakdown the switch closes and the battery forces the junction voltage back down to a lower value. This occurs over a period approximately equal to that of the transit time (assumed to be 200 psec). The switch then opens and the model is ready for another cycle of operation when the external circuit recharges the junction capacitance up to the level of breakdown.

The circuit and bias arrangement used for analyzing the behavior of the avalanche diode in a series resonant circuit is shown in Fig. III-3. In the experimental work the diode was biased in pulsed operation to avoid burnout at the high bias levels. At very low bias levels (a few mA) the diode would operate as a relaxation oscillator whose frequency was dependent on  $R_o$ ,  $C_o$ ,  $C_d$ , and the bias level. The tank circuit would ring at a frequency given by

$$f_1 = \frac{1}{2\pi \sqrt{L_o \left( \frac{C_o C_d}{C_o + C_d} \right)}} .$$

At the low bias levels the frequency of relaxation oscillations is much lower than this frequency. Both models were in reasonable agreement with the diode at the low bias levels.

As the bias level was increased the frequency of relaxation oscillations increased until they approached the resonant frequency of the tank circuit,  $f_2$ :

$$f_2 = \frac{1}{2\pi \sqrt{L_o C_o}} .$$

At this point the tank circuit would strongly couple to the diode and the circuit would resonate at frequency  $f_2$ . No RF power was observed at the frequency  $f_1$  at this point (~13 mA bias). This indicated that the diode must appear as an RF short during breakdown and it must be in breakdown for a considerable portion of the time in order to effectively short out the effects of the junction capacitance  $C_d$ . Both models also indicated this behavior. There also existed in the spectrum, however, relaxation oscillations at a frequency somewhat higher than  $f_1$ . These could be accounted for with the transient model (because of a rapid train of breakdowns), but not with the modified piecewise linear model (which had a breakdown repetition rate the same as frequency  $f_2$ ).

At larger bias levels (20-100 mA) the oscillations at frequency  $f_2$  increased in strength, while the intensity of the higher frequency relaxation oscillations appeared to go down. At these bias levels the modified piecewise linear model predicted that the circuit would cease to oscillate and that the diode would go into static breakdown and stay there. The transient model, on the other hand, predicted that the circuit would oscillate at frequency  $f_2$  and also very high-frequency relaxation oscillations (2-3 GHz) would be observed. The relaxation oscillations observed in the experimental circuit were

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approximately 0.6-0.7 GHz.

The circuit and bias arrangement used for the avalanche diode in a parallel resonant circuit is shown in Fig. III-4. At low bias levels the diode again operates as a relaxation

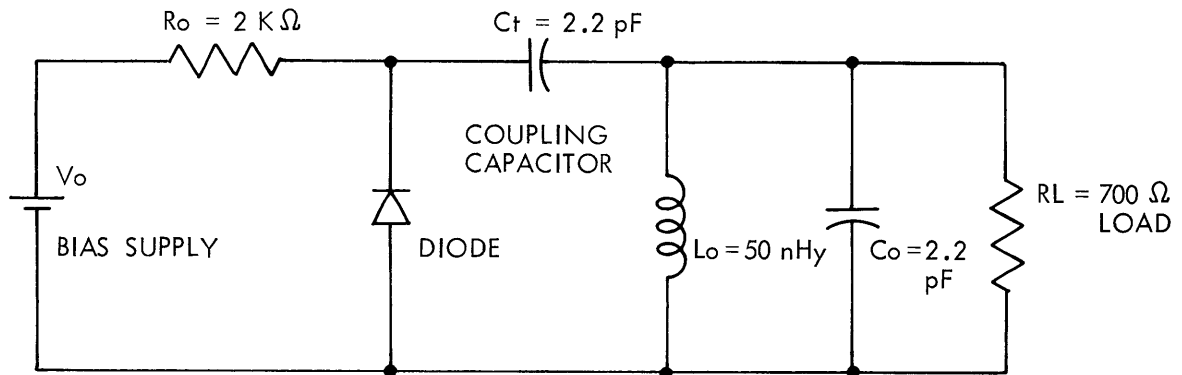


Fig. III-4. Avalanche diode in a parallel resonant circuit.

oscillator with the tank circuit ringing at a higher frequency  $f_3$  given by

$$f_3 = \frac{1}{2\pi \sqrt{L_o \left( C_o + \frac{C_t C_d}{C_t + C_d} \right)}}$$

Both models predicted these results.

As the bias was increased the relaxation oscillation frequency increased until it approached that of the resonant frequency of the tank circuit  $f_4$ , given by

$$f_4 = \frac{1}{2\pi \sqrt{L_o(C_o + C_t)}}$$

Up to this point both models were in agreement with the experimental results. At medium bias levels (12-15 mA) the junction capacitance appears to be shorted out by the diode breakdown and the tank circuit rings at frequency  $f_4$ .

At larger bias levels (20-100 mA) higher frequency relaxation oscillations can be observed in the spectrum. The intensity of oscillations at frequency  $f_4$  decreases with increasing bias until they are no longer observed (above bias levels of ~90 mA). The parallel tank circuit did not appear to couple well to the diode, especially at large bias levels. The higher frequency relaxation oscillations (0.6-0.7 GHz) increased in intensity with increasing bias levels. As before, the modified piecewise linear model predicted that the circuit would cease to oscillate at these bias levels and go into static breakdown. The behavior of the transient model agreed partially with the behavior of the diode. It

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predicted relaxation oscillations at frequencies of 2-3 GHz for these bias levels and oscillations of reduced intensity at frequency  $f_4$ .

In general, there appears to be more evidence to support the type of breakdown mechanism represented by the transient model than by the modified piecewise linear model. At low bias levels the behavior of both of the models was in agreement with experimental results. The modified piecewise linear model failed to predict the experimental behavior at larger bias levels. The behavior of the transient model was in partial agreement with the experimental results at all bias levels except at very large bias levels above 115 mA where the avalanche diode would cease to oscillate. It is felt that above this bias level the avalanche diode does actually go into static breakdown and stay there (although, up to this point, the transient model appears to be more valid). Further investigation into the actual electrodynamicics of these breakdown mechanisms is required, however, before conclusive proof of either mechanism can be presented.

R. E. Crochiere

