Time domain operation of the TRAPATT diode for picosecond-kilovolt pulse generation

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Operation of the trapped plasma avalanche transit time (TRAPATT) diode in the time domain is presented. When operated in the time domain, pulses with amplitudes greater than 1,000 V and risetimes well under 300 ps can be achieved. Selection of a diode for use as a TRAPATT diode is discussed. Experimental results demonstrate pulse generation with an amplitude of 2000 V into 50 Ω and a risetime of 200 ps using a single diode and a power MOSFET driving circuit.

I. INTRODUCTION

The trapped plasma avalanche transit time (TRAPATT) diode was developed as a pulsed high power microwave oscillator.[1,2] Oscillators built using TRAPATT diodes must operate at high power levels to generate the trapped plasma. The high currents involved tend to filament through the device causing "hot spots" and device failure. Since the device operates in the breakdown region a good portion of the oscillation period, fabrication while maintaining controlled, hard breakdown is desirable. If the breakdown voltage and device capacitances are not constant from device to device the external circuit design can be difficult. Currently the TRAPATT diode is used very little because of these problems with reliability, fabrication, circuit design, and because of the avalanche mechanism involved, phase noise.

Although, the traditional use of the TRAPATT diode is in oscillator design, the work presented here uses the diode in the time domain to generate high speed and high voltage pulses. Operation of the TRAPATT diode is at low pulse repetition frequencies (PRF), on the order of 1 kHz, with risetimes less than 300 ps and amplitudes greater than 1 kV. The pulses contain wide spectral content needed in many areas of instrumentation such as high speed photography, gating of microchannel plate image intensifiers,[3–5] and ultra-wideband radar.[6] Other researchers have reported similar behavior in devices[7–10] which have been called avalanche diodes.

This work will describe, for the first time, selection of a commercial diode for TRAPATT operation and the design of a driver circuit. These limitations, until now, have been the main reason low jitter pulse generators with kV level amplitudes and picosecond risetimes have not been widely available for use in physics research instruments.

II. OPERATION IN THE TIME DOMAIN

Figure 1 shows the basic scheme used to generate these picosecond-kilovolt signals. A pulse generator with an amplitude larger than the breakdown voltage of the diode is applied to the diode in the reverse direction. When the pulse is applied to the circuit the diode will first break down, i.e., the diode will look like a zener diode, and then if the amplitude of the driving signal is large enough, so that a large current flows in the circuit, the diode will go into second breakdown.

Second breakdown can be thought of as a change in diode voltage from the primary breakdown voltage to some much lower value. Since KVL must be maintained in the circuit this is usually accompanied by an increase in the current flowing through the device. Destruction of the device is usually associated with second breakdown. However, if the amount of energy passed through the diode is limited, destruction is avoided. This usually means narrow pulses, <10 ns, must be used. The transition from primary breakdown to second breakdown can occur in tens of picoseconds. During this time the trapped plasma is being formed within the diode.

If a $P^+N^-N^+$ diode is used as a TRAPATT diode then the formation of the electron-hole plasma begins at the P^+N^- junction and travels across the N^- region to the N^-N^+ junction leaving the N^- region filled with the trapped plasma, Fig. 2. The apparent velocity of the plasma should be much larger than the saturation velocity of electrons and holes in the semiconductor for proper operation. The plasma is formed by exciting electrons below the valence band into states above the conduction band. The result is generation of a gaseous conductor (plasma) in picoseconds. Externally this appears as a switch closing in a time dependent on the plasma formation.

III. REQUIREMENTS FOR GENERATION OF THE TRAPPED PLASMA

Following the above discussion it might be concluded that the input pulse risetime is not critical to the operation of the circuit. This, however, is not the case. Second breakdown (plasma formation) is triggered by a current level. That is, when the device is in primary breakdown the current flowing in the diode must reach a critical level, I_{crit}, for second breakdown to occur. Also the velocity of the plasma, v_z, is dependent on the current level present when the diode begins to go into second breakdown. This was derived by[1] assuming the diode was driven with a constant current source as

$$v_z=\frac{I}{qN_DA}, \tag{1}$$

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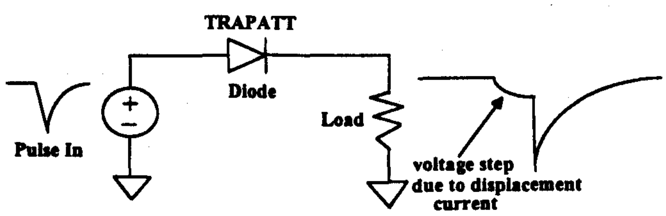

FIG. 1. Schematic diagram of circuit using TRAPATT diode in the time domain.

where I is the current through the diode, q is electron charge, N_D is doping concentration of the N^- region, and A is the cross sectional area. The larger the current flowing in the diode, the faster the plasma will sweep across the device and thus the switch will close in less time. Since v_z should be greater than the saturation velocity of carriers in the semiconductor, v_s, the critical current density is given by setting the saturation velocity equal to the plasma velocity, or

$$I_{\text{crit}} = v_S q N_D A. \tag{2}$$

This equation is useful in understanding how the various diode parameters affect I_{crit}. However, from a circuit design point of view an alternate description of the maximum input transition time of the drive signal is desirable. The current flowing in the diode prior to breakdown is a displacement current due to the diode junction capacitance. The magnitude of this displacement current is a function of diode capacitance, input pulse transition time, and load impedance. As a general rule, the input pulse transition time should be short compared to the time it takes carriers to drift across the N^- region at their saturated velocity. As an example, if the diode's N^- region length is 300 μm and the carriers travel at their saturated velocity of 10^7 cm/s the time the carriers will take to traverse the N^- region is 3 ns. The input pulse transition time should be less than 3 ns. Also the load impedance should be small compared to the diode junction capacitance's reactance. This ensures that the majority of the driving voltage is dropped across the diode prior to breakdown.

IV. SELECTING A DIODE

The major factors encountered when selecting a diode for operation as a TRAPATT diode are availability, reliability, sharpness of breakdown voltage, diode capacitance, package type, and length of N^- or P^- regions. The diode selected should be low cost and widely available. The reliability is directly related to the width of the pulses the diode

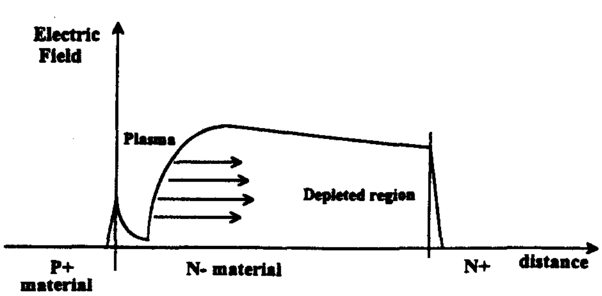

FIG. 2. Illustration showing formation of plasma with the TRAPATT diode.

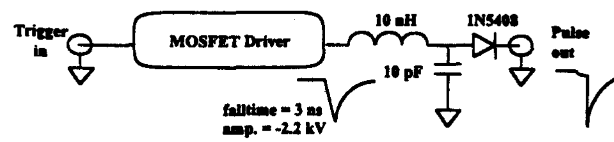

FIG. 3. Schematic diagram of TRAPATT pulse generator.

is used with. In general the narrower the pulse the longer the lifetime of the diode. The breakdown voltage of the diode should be very sharp. The transition displayed on a curve tracer should be a right angle or in other words hard breakdown.

The diode length, capacitance, and package type are related. First consider using a common diode such as the 1N4148. The length of the lightly doped region is on the order of 10 μm, so that the maximum input risetime of the driving source voltage is 100 ps following the discussion of the previous section. The breakdown voltage is on the order of 100 V. Design of a driver to deliver a pulse with an amplitude greater than 100 V and a risetime of under 100 ps can be difficult. Also the cross sectional area of the 1N4148 diode is relatively small so that the width of the input pulse is very critical.

In general, large rectifier diodes such as the 1N5408 offer the best choice for a TRAPATT diode. The large area dissipates heat well helping with reliability while the long diode length eases requirements on the driving circuit. The experimental results presented in this paper use a 1N5408. For the selected diode a driver must be designed which will generate a pulse greater than 2000 V and a risetime of 3 ns. It is also desirable to have negligible jitter. The absence of jitter makes viewing the pulse simpler on a sampling scope. Currently the best device available to generate jitter free nanosecond rise pulses with kV level amplitudes is the power MOSFET.[11,12]

V. EXPERIMENTAL RESULTS

The circuit shown in Fig. 3 was used to generate the waveform shown in Fig. 4. The amplitude of this pulse was approximately 2 kV with a risetime of 200 ps into 50 Ω. Pulse jitter was negligible. The driver circuit consisted of a Marx bank of power MOSFETs similar to the one described in Ref. 13. The output of the driver was a 2.2 kV pulse with

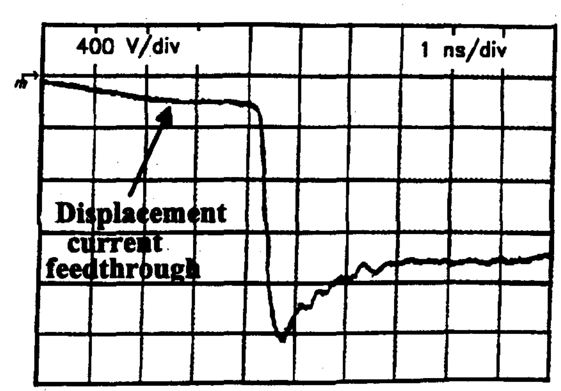

FIG. 4. Output of circuit shown in Fig. 3.

a 3 ns risetime. The 10 nH inductance in Fig. 3 is used to isolate the diode from the driver when the diode switches. The 10 pF capacitor is used to store the charge needed for the load when the diode switches. Figure 4 shows that before the fast edge occurs a displacement current is present. This is the displacement current discussed earlier. The particular diode used had a zero bias junction capacitance of 100 pF and a breakdown voltage of 1400 V. The epoxy coating was removed from the diode so as to minimize the inductance in series with the diode.

The circuit was fabricated on a copper coated glass epoxy board to give a good ground plane. The 10 pF capacitor was actually made from a 1 in. square piece of board material to minimize lead inductance. Measuring these signals can be difficult. The output coax was soldered to the ground plane over a length of 5 in and then wrapped around a ferrite core to reduce currents traveling on the outside of the outer conductor.

A faster input signal will cause the displacement current to increase and thus the step voltage shown in Fig. 4 will become larger. The switching time will decrease with a faster input driving voltage. To achieve sub 100 ps transition times more than one TRAPATT diode may be used. If the wave form shown in Fig. 4 is fed to a second diode the resulting output signal transition time would be limited by the parasitics of the circuit. The main drawback is the increase in the displacement current as the speed is increased.

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