-3 TRAPATT DIODES

8-3-1 Physical Structures

The abbreviation TRAPATT stands for *trapped plasma avalanche triggered transit* mode, a mode first reported by Prager et al. [7]. It is a high-efficiency microwave generator capable of operating from several hundred megahertz to several gigahertz. The basic operation of the oscillator is a semiconductor p-n junction diode reverse-biased to current densities well in excess of those encountered in normal avalanche operation. High-peak-power diodes are typically silicon n^+-p-p^+ (or p^+-n-n^+) structures with the n-type depletion region width varying from 2.5 to 12.5 μm. The doping of the depletion region is generally such that the diodes are well "punched through" at breakdown; that is, the dc electric field in the depletion region just prior to breakdown is well above the saturated drift-velocity level. The device's p^+ region is kept as thin as possible at 2.5 to 7.5 μm. The TRAPATT diode's diameter ranges from as small as 50 μm for CW operation to 750 μm at lower frequency for high-peak-power devices.

8-3-2 Principles of Operation

Approximate analytic solutions for the TRAPATT mode in p^+-n-n^+ diodes have been developed by Clorfeine et al. [8] and DeLoach [9] among others. These analyses have shown that a high-field avalanche zone propagates through the diode and fills the depletion layer with a dense plasma of electrons and holes that become trapped in the low-field region behind the zone. A typical voltage waveform for the TRAPATT mode of an avalanche p^+-n-n^+ diode operating with an assumed square-wave current drive is shown in Fig. 8-3-1. At point A the electric field is uniform throughout the sample and its magnitude is large but less than the value required for avalanche breakdown. The current density is expressed by

$$J = \epsilon_s \frac{dE}{dt} \tag{8-3-1}$$

where ϵ_s is the semiconductor dielectric permittivity of the diode.

At the instant of time at point A, the diode current is turned on. Since the only charge carriers present are those caused by the thermal generation, the diode initially charges up like a linear capacitor, driving the magnitude of the electric field above the breakdown voltage. When a sufficient number of carriers is generated, the particle current exceeds the external current and the electric field is depressed throughout the depletion region, causing the voltage to decrease. This portion of the cycle is shown by the curve from point B to point C. During this time interval the electric field is sufficiently large for the avalanche to continue, and a dense plasma of electrons and holes is created. As some of the electrons and holes drift out of the ends of the depletion layer, the field is further depressed and "traps" the remaining plasma. The voltage decreases to point D. A long time is required to remove the plasma because the total plasma charge is large compared to the charge per unit time

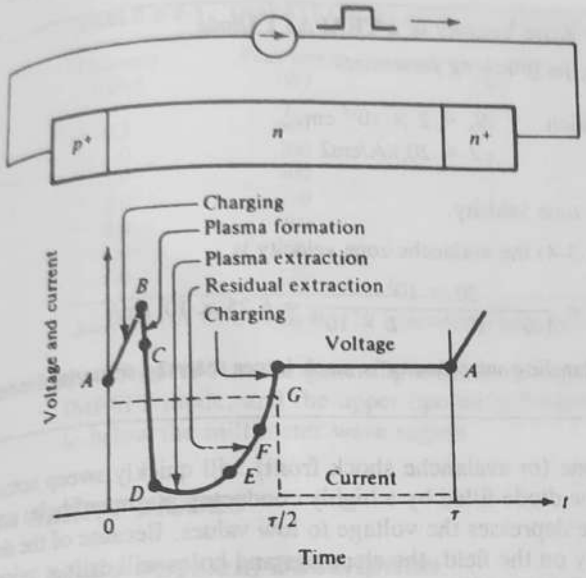

Figure 8-3-1 Voltage and current waveforms for TRAPATT diode. (*After A. S. Clorfeine et al. [8]; reprinted by permission of RCA Laboratory.*)

in the external current. At point E the plasma is removed, but a residual charge of electrons remains in one end of the depletion layer and a residual charge of holes in the other end. As the residual charge is removed, the voltage increases from point E to point F. At point F all the charge that was generated internally has been removed. This charge must be greater than or equal to that supplied by the external current; otherwise the voltage will exceed that at point A. From point F to point G the diode charges up again like a fixed capacitor. At point G the diode current goes to zero for half a period and the voltage remains constant at V_A until the current comes back on and the cycle repeats. The electric field can be expressed as

$$E(x, t) = E_m - \frac{qN_A}{\epsilon_s}x + \frac{Jt}{\epsilon_s} \tag{8-3-2}$$

where N_A is the doping concentration of the n region and x is the distance.

Thus the value of t at which the electric field reaches E_m at a given distance x into the depletion region is obtained by setting $E(x, t) = E_m$, yielding

$$t = \frac{qN_A}{J}x \tag{8-3-3}$$

Differentiation of Eq. (8-3-3) with respect to time t results in

$$v_z \equiv \frac{dx}{dt} = \frac{J}{qN_A} \tag{8-3-4}$$

where v_z is the avalanche-zone velocity.

Example 8-3-1: Avalanche-Zone Velocity of a TRAPATT Diode

A TRAPATT diode has the following parameters:

Doping concentration: $N_A = 2 \times 10^{15}\ \text{cm}^{-3}$
Current density: $J = 20$ kA/cm2

Calculate the avalanche-zone velocity.

Solution From Eq. (8-3-4) the avalanche-zone velocity is

$$v_z = \frac{J}{qN_A} = \frac{20 \times 10^3}{1.6 \times 10^{-19} \times 2 \times 10^{15}} = 6.25 \times 10^7\ \text{cm/s}$$

This means that the avalanche-zone velocity is much larger than the scattering-limited velocity.

Thus the avalanche zone (or avalanche shock front) will quickly sweep across most of the diode, leaving the diode filled by a highly conductng plasma of holes and electrons whose space charge depresses the voltage to low values. Because of the dependence of the drift velocity on the field, the electrons and holes will drift at velocities determined by the low-field mobilities, and the transit time of the carriers can become much longer than

$$\tau_s = \frac{L}{v_s} \tag{8-3-5}$$

where v_s is the saturated carrier drift velocity.

Thus the TRAPATT mode can operate at comparatively low frequencies, since the discharge time of the plasma—that is, the rate Q/I of its charge to its current—can be considerably greater than the nominal transit time τ_s of the diode at high field. Therefore the TRAPATT mode is still a transit-time mode in the real sense that the time delay of carriers in transit (that is, the time between injection and collection) is utilized to obtain a current phase shift favorable for oscillation.

8-3-3 Power Output and Efficiency

RF power is delivered by the diode to an external load when the diode is placed in a proper circuit with a load. The main function of this circuit is to match the diode effective negative resistance to the load at the output frequency while reactively terminating (trapping) frequencies above the oscillation frequency in order to ensure TRAPATT operation. To date, the highest pulse power of 1.2 kW has been obtained at 1.1 GHz (five diodes in series) [10], and the highest efficiency of 75% has been achieved at 0.6 GHz (11). Table 8-3-1 shows the current state of TRAPATT diodes [12].

The TRAPATT operation is a rather complicated means of oscillation, however, and requires good control of both device and circuit properties. In addition,

TABLE 8-3-1 TRAPATT OSCILLATOR CAPABILITIES

Frequency (GHz)	Peak power (W)	Average power (W)	Operating voltage (V)	Efficiency (%)
0.5	600	3	150	40
1.0	200	1	110	30
1.0	400	2	110	35
2.0	100	1	80	25
2.0	200	2	80	30
4.0	100	1	80	20
8.0	50	1	60	15

Source: After W. E. Wilson [12]; reprinted by permission of Horizon House.

the TRAPATT mode generally exhibits a considerably higher noise figure than the IMPATT mode, and the upper operating frequency appears to be practically limited to below the millimeter wave region.