IMPATT DIODES

8-2-1 Physical Structures

A theoretical Read diode made of an n^+-p-i-p^+ or p^+-n-i-n^+ structure has been analyzed. Its basic physical mechanism is the interaction of the impact ionization avalanche and the transit time of charge carriers. Hence the Read-type diodes are called IMPATT diodes. These diodes exhibit a differential negative resistance by two effects:

1. The impact ionization avalanche effect, which causes the carrier current $I_0(t)$ and the ac voltage to be out of phase by 90°
2. The transit-time effect, which further delays the external current $I_e(t)$ relative to the ac voltage by 90°

The first IMPATT operation as reported by Johnston et al. [4] in 1965, however, was obtained from a simple p-n junction. The first real Read-type IMPATT diode was reported by Lee et al. [3], as described previously. From the small-signal theory developed by Gilden [5] it has been confirmed that a negative resistance of the IMPATT diode can be obtained from a junction diode with any doping profile. Many IMPATT diodes consist of a high doping avalanching region followed by a drift region where the field is low enough that the carriers can traverse through it without avalanching. The Read diode is the basic type in the IMPATT diode family. The others are the one-sided abrupt p-n junction, the linearly graded p-n junction (or double-drift region), and the p-i-n diode, all of which are shown in Fig. 8-2-1. The principle of operation of these devices, however, is essentially similar to the mechanism described for the Read diode.

8-2-2 Negative Resistance

Small-signal analysis of a Read diode results in the following expression for the real part of the diode terminal impedance [5]:

$$R = R_s + \frac{2L^2}{v_d \epsilon_s A} \frac{1}{1 - \omega^2/\omega_r^2} \frac{1 - \cos\theta}{\theta} \qquad (8\text{-}2\text{-}1)$$

where R_s = passive resistance of the inactive region
v_d = carrier drift velocity
L = length of the drift space-charge region
A = diode cross section
e_s = semiconductor dielectric permittivity

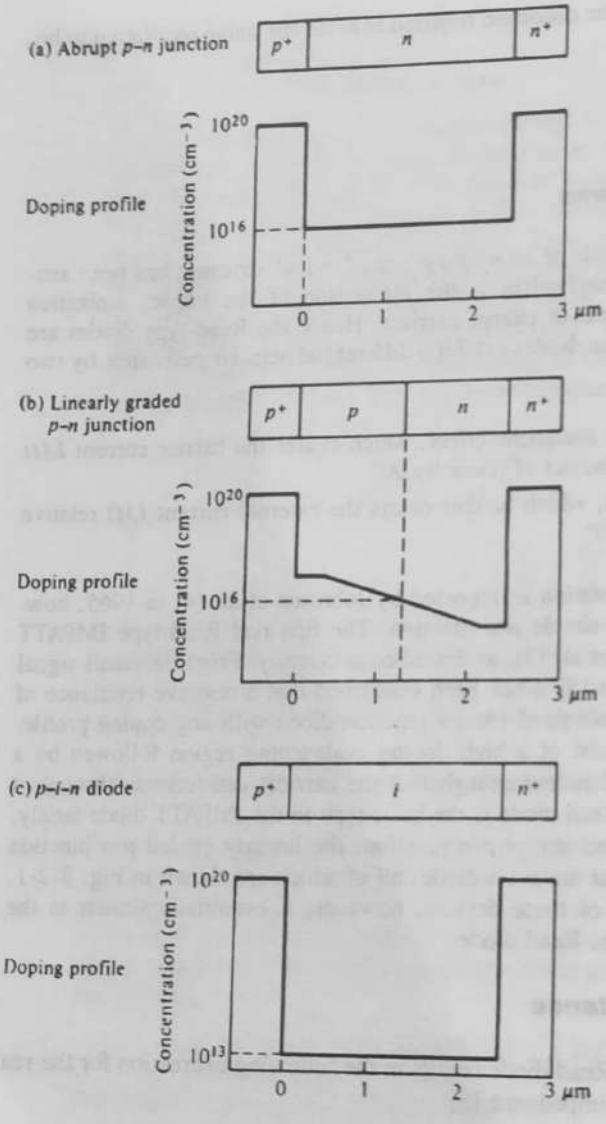

Figure 8-2-1 Three typical silicon IMPATT diodes. (*After R. L. Johnston et al. [4]; reprinted by permission of the Bell System, AT&T Co.*)

Moreover, θ is the transit angle, given by

$$\theta = \omega\tau = \omega\frac{L}{v_d} \tag{8-2-2}$$

and ω_r is the avalanche resonant frequency, defined by

$$\omega_r \equiv \left(\frac{2\alpha' v_d I_0}{\epsilon_s A}\right)^{1/2} \tag{8-2-3}$$

In Eq. (8-2-3) the quantity α' is the derivative of the ionization coefficient with respect to the electric field. This coefficient, the number of ionizations per centimeter produced by a single carrier, is a sharply increasing function of the electric field. The variation of the negative resistance with the transit angle when $\omega > \omega_r$ is plotted in Fig. 8-2-2. The peak value of the negative resistance occurs near $\theta = \pi$. For transit angles larger than π and approaching $3\pi/2$, the negative resistance of the diode decreases rapidly. For practical purposes, the Read-type IMPATT diodes work well only in a frequency range around the π transit angle. That is,

$$f = \frac{1}{2\tau} = \frac{v_d}{2L} \tag{8-2-4}$$

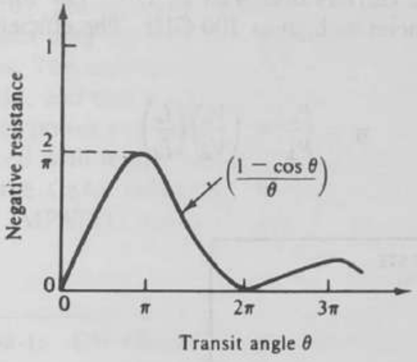

Figure 8-2-2 Negative resistance versus transit angle.

8-2-3 Power Output and Efficiency

At a given frequency the maximum output power of a single diode is limited by semiconductor materials and the attainable impedance levels in microwave circuitry. For a uniform avalanche, the maximum voltage that can be applied across the diode is given by

$$V_m = E_m L \tag{8-2-5}$$

where L is the depletion length and E_m is the maximum electric field. This maximum applied voltage is limited by the breakdown voltage. Furthermore, the maximum current that can be carried by the diode is also limited by the avalanche breakdown process, for the current in the space-charge region causes an increase in the electric field. The maximum current is given by

$$I_m = J_m A = \sigma E_m A = \frac{\epsilon_s}{\tau} E_m A = \frac{v_d \epsilon_s E_m A}{L} \tag{8-2-6}$$

Therefore the upper limit of the power input is given by

$$P_m = I_m V_m = E_m^2 \epsilon_s v_d A \tag{8-2-7}$$

The capacitance across the space-charge region is defined as

$$C = \frac{\epsilon_s A}{L} \tag{8-2-8}$$

Substitution of Eq. (8-2-8) in Eq. (8-2-7) and application of $2\pi f\tau = 1$ yield

$$P_m f^2 = \frac{E_m^2 v_d^2}{4\pi^2 X_c} \tag{8-2-9}$$

It is interesting to note that this equation is identical to Eq. (5-1-60) of the power-frequency limitation for the microwave power transistor. The maximum power that can be given to the mobile carriers decreases as $1/f^2$. For silicon, this electronic limit is dominant at frequencies as high as 100 GHz. The efficiency of the IMPATT diodes is given by

$$\eta = \frac{P_{ac}}{P_{dc}} = \left(\frac{V_a}{V_d}\right)\left(\frac{I_a}{I_d}\right) \tag{8-2-10}$$

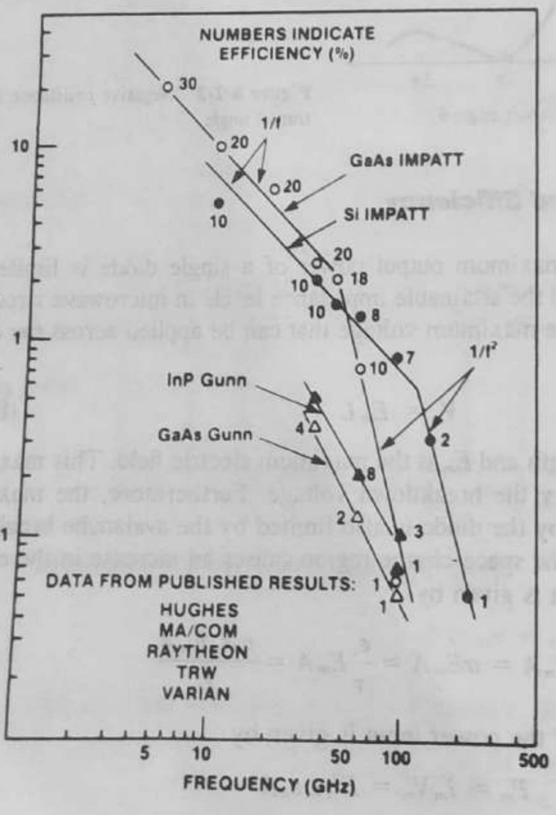

Figure 8-2-3 State-of-the-art performance for GaAs and Si IMPATTs. *(From H. Hieslmair, et al. [6]; reprinted by permission of* Microwave Journal.)

For an ideal Read-type IMPATT diode, the ratio of the ac voltage to the applied voltage is about 0.5 and the ratio of the ac current to the dc current is about $2/\pi$, so that the efficiency would be about $1/\pi$ or more than 30%. For practical IMPATT diodes, however, the efficiency is usually less than 30% because of the space-charge effect, the reverse-saturation-current effect, the high-frequency-skin effect, and the ionization-saturation effect.

IMPATT diodes are at present the most powerful CW solid-state microwave power sources. The diodes have been fabricated from germanium, silicon, and gallium arsenide and can probably be constructed from other semiconductors as well. IMPATT diodes provide potentially reliable, compact, inexpensive, and moderately efficient microwave power sources.

Figure 8-2-3 shows the latest state-of-the-art performance for GaAs and Si IMPATTs [6]. The numbers adjacent to the data points indicate efficiency in percent. Power output data for both the GaAs and Si IMPATTs closely follow the $1/f$ and $1/f^2$ slopes. The transition from the $1/f$ to the $1/f^2$ slope for GaAs falls between 50 and 60 GHz, and that for Si IMPATTs between 100 and 120 GHz. GaAs IMPATTs show higher power and efficiency in the 40- to 60-GHz region whereas Si IMPATTs are produced with higher reliability and yield in the same frequency region. On the contrary, the GaAs IMPATTs have higher powers and efficiencies below 40 GHz than do Si IMPATTs. Above 60 GHz the Si IMPATTs seem to outperform the GaAs devices.

Example 8-2-1: CW Output Power of an IMPATT Diode

An IMPATT diode has the following parameters:

Carrier drift velocity:	$v_d = 2 \times 10^7$ cm/s
Drift-region length:	$L = 6\ \mu$m
Maximum operating voltage:	$V_{0\max} = 100$ V
Maximum operating current:	$I_{0\max} = 200$ mA
Efficiency:	$\eta = 15\%$
Breakdown voltage:	$V_{bd} = 90$ V

Compute: **(a)** the maximum CW output power in watts; **(b)** the resonant frequency in gigahertz.

Solution

a. From Eq. (8-2-10) the CW output power is

$$P = \eta P_{dc} = 0.15 \times 100 \times 0.2 = 3\text{W}$$

b. From Eq. (8-2-4) the resonant frequency is

$$f = \frac{v_d}{2L} = \frac{2 \times 10^5}{2 \times 6 \times 10^{-6}} = 16.67 \text{ GHz}$$