CALIFORNIA POLYTECHNIC STATE UNIVERSITY

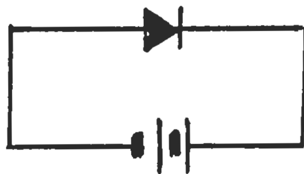
Solid State Physics Laboratory

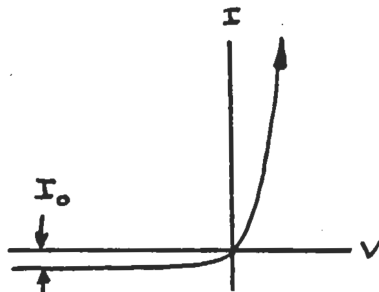
Experiment 15: TEMPERATURE DEPENDENCE OF THE SATURATION CURRENT OF A JUNCTION DIODE

SCOPE

The determination of the temperature dependence of the saturation current in reverse biased pn junction diodes (silicon and germanium) in order to determine the dominant contribution to the saturation current.

INTRODUCTION





When a pn junction diode is reverse biased, a small current flows which is nearly independent of the bias potential. This current (called the "saturation current") appears in the characteristic voltage-current relationship as I_o. The current in the circuit is given by

$$I(V) = I_o\left[\exp(eV/kT) - 1\right] \quad (1)$$

where V is the applied bias voltage (which would be negative in reverse bias), T is the absolute temperature, e is the electron charge, and k is Boltzmann's constant.

The saturation current is a combination of the generation current caused by thermal generation of electron hole pairs within the depletion region of the diode and the diffusion current due to minority carriers in the n and p regions diffusing across the depletion region. Although the saturation current is voltage independent, it does depend on temperature since both the current contributions depend on thermally stimulated carriers.

A. The Generation Current

The generation current contribution to the saturation current comes from the electron-hole pairs that are thermally generated within the depletion region. The description of the temperature dependence of I assumes that the depletion region behaves essentially like an intrinsic semiconductor when the diode is reverse biased at sufficiently low temperatures. That is, the conductivity of the depletion region - and hence the current flow through it - should be proportional to the intrinsic carrier concentration

$$n_i(T) = 2(mkT/2\pi\hbar^2)^{3/2}\exp(-E_g/2kT) \quad (2)$$

where E_g is the gap energy between the valence and conduction bands. The generation current will thus be proportional to the exponential factor, or

$$I_{gen}(T) \sim \exp(-E_g/2kT) \quad (3)$$

The generation current is the dominant contributor to the saturation current when the intrinsic carrier concentration $n_i(T)$ is so small compared to the dopant contributed carrier concentrations within the n and p regions so that the diffusion of minority carriers across the depletion region is negligible and the depletion region behaves like an intrinsic semiconductor. This condition is satisfied better the larger the ratio E_g/kT.

B. **Diffusion Current**

The diffusion current is due to minority carriers within each region of the diode diffusing to the other region across the junction. Electrons in the p-region which diffuse into the depletion region are swept to toward the n-regin by the junction field. Likewise, holes in the n-region which diffuse into the depletion region are swept to the p-region by the junction field. This diffusion current is in the reverse bias direction.

The diffusion current contribution to the reverse bias current can be significant if the minority carrier concentrations within the n and p regions is large. Under those conditions the law of mass action holds and is given by the relationship $np=n_i^2(T)$. For either light doping or sufficiently high temperature, the Fermi level will be sufficiently far from the band edge that the law of mass action applies. Or, stated differently, this condition is satisfied more effectively the smaller the ratio E_g/kT.

If these conditions are satisfied for both the n and p regions of a junction diode, then the concentration of electrons in the p-region and holes in the n-region can be expressed as $n_p=n_i^2(T)/p_p$ and $p_n= n_i^2(T)/n_n$, respectively. But the concentration of electrons in the n-region is essentially equal to the donor concentration (N_d). Similarly, the concentration of holes in the p-region is essentially the acceptor state concentration (N_a). The diffusion current is thus proportional to $n_i^2(T)$. Since $n_i(T)$ is proportional to $\exp(-E_g/2kT)$, the saturation current must be proportional to $\exp(-E_g/kT)$ under the conditions that yield the law of mass action. That is,

$$I_{diff}(T) \sim \exp(-E_g/kT) \qquad (4)$$

The current described in this way is due to diffusion of carriers across the depletion region (ie, electron diffusion from p to n).

Which of the above descriptions correctly describes the temperature dependence of the saturation current of a diode depends on which of the contributions is dominant. Of course, the saturation current is actually a combination of both the reverse diffusion and generation currents. So the correct description is given in the form

$$I_o = I_{diff} + I_{gen}$$

$$= [\text{constants}]\, n_i^2(T) + [\text{constants}]\, n_i(T)$$

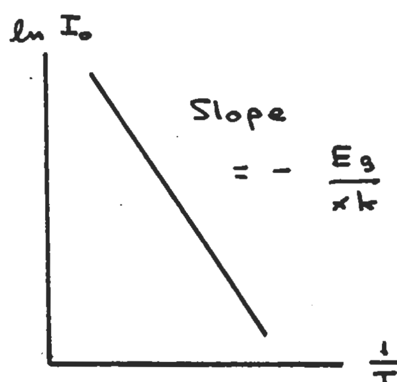
$$= [\quad]\exp(-E_g/kT) + [\quad]\exp(-E_g/2kT)$$

The temperature dependence of the saturation current can be written approximately in the form

$$I_o = [\text{constants}] \exp(-E_g/xkT) \tag{5}$$

where the parameter x is between 1 and 2. If the diffusion current dominates the saturation current, then x=1. If the generation current dominates, then x=2.

The characteristic exponential dependence can be verified by graphing the logarithm of I_o versus the inverse of the absolute temperature. That is



$$\ln I_o = [\text{const}] - E_g/(xkT) \tag{6}$$

where x depends on which of the contributions to the saturation current dominates. But lnI is thus linear in (1/T) with a slope of $-E_g/xk$. So determining the temperature dependence of the saturation current can both verify the general functional dependence and obtain the value of x in the denominator of the exponential. That is, the experiment can determine which of the contributions is dominant.

PROCEDURE

Using a microammeter, monitor the saturation current for both a silicon and a germanium diode as a function of temperature from about ice-point to about 150 C. Allow the samples to reach thermal equilibrium with the oil bath at each temperature before taking measurements.

REPORT

1. Graph the saturation current for each sample as a function of temperature.

2. Graph the natural logarithm of the saturation current for each sample as a function of the reciprocal of the absolute temperture. Determine the experimental value of the coefficient x (and its uncertainty) for each sample.

3. Discuss whether the expected exponential dependence of the saturation current on temperature given in equation (5) are verified by your experiment. Based on your experimental results, discuss which contribution to the saturation current is dominant in each diode. How does your experimental determination of the temperature dependence of I_o compare with the published temperature dependence for silicon and germanium diodes? Explain any discrepancies between your experimental results and the expected results.