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THE EFFECT OF TRAPPING STATES ON TUNNELING IN METAL-SEMICONDUCTOR JUNCTIONS

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The tunneling behavior of Schottky barriers has been investigated by several authors. The $I-V$ characteristics exhibit an exponential form in the forward direction which can be used to determine the energy vs complex momentum dispersion relation for charge carriers in the forbidden gap. In this paper we show that under proper conditions the presence of traps can increase the tunneling probability and result in a reduction in the slope of the log I vs V characteristic by a factor of 2.

Schottky barriers were fabricated by evaporating palladium onto n-type CdTe, prepared by cleaving on the (110) crystal plane and immediately placing the crystal in an ion-pumped vacuum system. The palladium was evaporated through a metal mask in a vacuum of 10^{-7} Torr. The carrier concentration was determined in each case by (capacitance)$^{-2}$ vs voltage plots. These plots showed no significant change from room temperature to 77°K.

The $I-V$ characteristics of diodes having different carrier concentrations are shown in Fig. 1. The upper portion of the curves agrees (±10%) with that expected from tunneling calculations,[1,2] including a slight temperature dependence, presented by Padovani and Stratton[1] where

$$I \propto \exp\{-s(\varphi_B - V - \xi)\} \qquad (1)$$

and

$$s = \frac{2}{\hbar}\left(\frac{m^*\epsilon}{N_D}\right)^{1/2} \tanh\left[\frac{q}{kT}\,\frac{\hbar}{2}\left(\frac{N_D}{m^*\epsilon}\right)^{1/2}\right]. \qquad (2)$$

Here I is the current, φ_B the barrier energy, V the applied voltage, ξ the Fermi energy, $\hbar$ Planck's constant, m^* the effective mass of the electron, ϵ the dielectric constant of the semiconductor, N_D the carrier concentration, q the charge on the electron, k Boltzman's constant, and T the absolute temperature.

The lower portion of the log I vs V curves differs by a factor of 2 (±10%) from that predicted by Eq. (1). We attribute this change in slope to tunneling via an intermediate state as illustrated in Fig. 2.

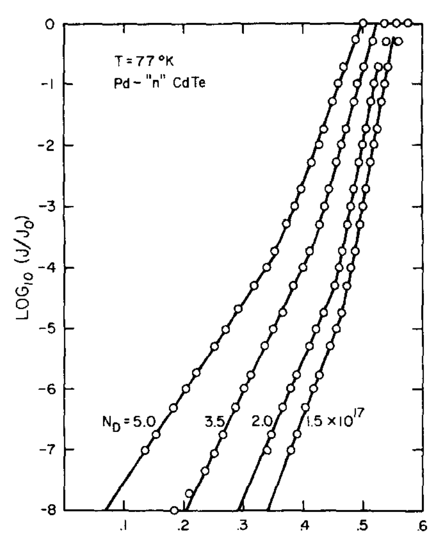

Fig. 1. $I-V$ characteristics of Pd "n" CdTe barriers for several carrier concentrations (J_0 = 1 A/cm^2).

The tunneling rate R (and hence the current) arising from electron tunneling through the forbid-

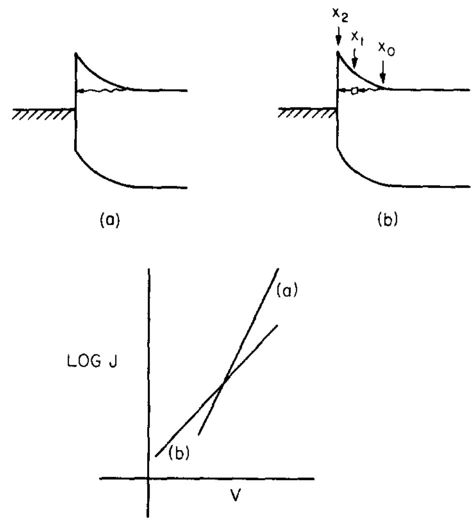

Fig. 2. Tunneling through a Schottky barrier with and without trapping center.

den gap[3-5] of a semiconductor is of the form[6]

$$R \propto \exp\left\{-2\int_{x_0}^{x_2} k\,dx\right\}\ , \tag{3}$$

where k is the complex momentum wavevector of the electron. The integral is taken from the conduction band at x_0 to the metal at x_2.

Padovani and Stratton[1] have completed the detailed calculation for tunneling through a Schottky barrier by assuming a parabolic energy momentum dispersion relation with the result given in Eq. (1). However, if traps are present we must also concern ourselves with a two-step tunneling process with the trap as an intermediate state. In the forward direction, (1) the electron tunnels from the semiconductor conduction band to the state and then (2) from the state to the metal. If the concentration of states is given by N_t and F is the probability of occupation of the state by an electron, then the number of occupied states is $N_t F$. Rewriting Eq. (3) in terms of the new limits we find that the rates for the two steps are

$$R_1 = C_1 N_t (1-f)\exp\left\{-2\int_{x_0}^{x_1} k\,dx\right\} \tag{4}$$

and

$$R_2 = C_2 N_t f \exp\left\{-2\int_{x_1}^{x_2} k\,dx\right\}\ , \tag{5}$$

where the factors C_1 and C_2 are slowly varying functions of the voltage, etc.

Under steady-state conditions, F will adjust itself until two rates are equal. Thus

$$R_1 = R_2 = \frac{C_1 C_2 N_t \exp\left(-2\left\{\int_{x_2}^{x_1} k\,dx + \int_{x_1}^{x_2} k\,dx\right\}\right)}{C_1 \exp\left\{-2\int_{x_0}^{x_1} k\,dx\right\} + C_2 \exp\left\{-2\int_{x_1}^{x_2} k\,dx\right\}}\ . \tag{6}$$

Equation (6) represents a peaked function which, provided C_1 and C_2 are not too different, attains its maximum value when

$$\exp\left\{-2\int_{x_1}^{x_2} k\,dx\right\} = \exp\left\{-2\int_{x_0}^{x_1} k\,dx\right\}\ . \tag{7}$$

The rate for the completed transition will be proportional to the peak value of Eq. (6), which is just the square root of the expression for single-step tunneling.

$$R \propto \exp\left\{-\int_{x_0}^{x_2} k\,dx\right\}\ . \tag{8}$$

The number of traps and their distribution in energy will determine the magnitude and range over which Eq. (8) is valid. If states are available in the context described above, we can repeat the procedure used by Padovani and Stratton[1] and show that the current is now of the form

$$I \propto \exp\{-\tfrac{1}{2}s(\varphi_B - V - \xi)\}\ . \tag{9}$$

The slope of the $\log I$ vs V curves has been reduced to $1/2\,S$. An analogous situation is known to occur in p–n junctions [7-9] at low biases for the case of recombination via intermediate states in the space-charge region. There the states change the slope of the $\log I$ vs V curve from q/kT to $q/2kT$.

The wide range of energy over which tunneling occurs via intermediate states can be attributed to thermal broadening of the peak of Eq. (6) at 77°K. The diode $I-V$ characteristics began to exhibit structure in the low applied voltage range when the samples were cooled to 4.2°K, thus confirming that trapping states are responsible for the observed behavior. The method described here is a potentially powerful technique for studying the distribution in energy of traps in these materials. The current should show a maximum (or at least a minimum in $d\log I/dV$), where $\varphi - V - \xi$ is equal to twice the trap energy [Eq. (7)].

In samples fabricated from a different ingot of CdTe the two-step tunneling process was found to dominate the entire measurable forward $I-V$ characteristic. Guard-ring experiments and area-dependent $I-V$ characteristics indicated that anomalous edge effects were not responsible for the observed behavior. Thus we have shown that the presence of traps can under the proper conditions significantly alter the tunneling characteristics of a Schottky barrier diode, and can be unambiguously identified by the slope of the $\log I$ vs V plot.

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TIME AVERAGE HOLOGRAPHY EXTENDED*

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It is demonstrated that the usefulness of time-average holography in analyzing vibration can be extended by modulating the reference beam.

Powell and Stetson have shown that time-average holography can be used to analyze vibrations.[1] This letter will describe how time-average holography can be extended in its range of usefulness by modulating the reference beam.

A basic concept in time-average holography is that a sinusoidally vibrating object will phase modulate light reflected from it with a modulation depth proportional to the amplitude of vibration. Consider a point, with coordinate vector **x**, on the vibrating object. Light scattered from this point to a point on the photographic plate will be phase modulated by the function $a(\mathbf{x})\cos[\omega t + \alpha(\mathbf{x})]$, where $a(\mathbf{x})$ is the modulation depth, ω the angular frequency of vibration, and $\alpha(\mathbf{x})$ the phase of modulation. Powell and Stetson demonstrated that the brightness of the reconstructed point is proportional to $J_0^2(a)$, where $J_0(a)$ is the zero-order Bessel function. Thus fringes are formed on the reconstructed object from which the vibration amplitudes of the object can be analyzed. However, note that as the amplitude of vibration increases, the fringe peaks decrease, and it becomes difficult to analyze the vibrations. Further note that the phase information $\alpha(\mathbf{x})$ is lost.

Both of these deficiencies can be corrected by phase modulating the reference beam with the function $b\cos(\omega t + \beta)$. It can then be shown[2] that the object point will reconstruct with a brightness proportional to $J_0^2(c)$, where c is given by the cosine law

$$c^2 = a^2 + b^2 - 2ab\cos(\alpha - \beta).$$

Thus the fringes are no longer formed about zero vibration amplitude, but about a vibration amplitude determined by the modulation depth and phase of the reference beam.

These results have been experimentally demonstrated by observing the mode structure of a resonant crystal. A 1-in.-cube ADP crystal (0° cut) was electrically excited into standing shear-wave modes. Such shear modes have been studied by crossed polaroid techniques.[3] Figure 1(a) shows the fifth-order shear mode in a crossed polaroid system.

For the hologram exposure collimated light is directed along the z axis of the crystal and is plane polarized at 45° to the crystal's x and y axes. Thus the output light remains plane polarized, and is phase modulated by the changing index of refraction. The output light is then incident onto a diffusing plate, and a hologram is made of the diffusing plate. Figure 1(b) shows the virtual image reconstructed from a normal time-average hologram of the fifth-order shear mode. Note that the nulls reconstruct brightest. Figure 1(c) is the reconstruction when the reference beam is modulated with a modulation depth and phase approximately equal to the peak of the central lobe of the fifth-order shear mode. Note that the central lobe is brightest, while the adjacent lobes, vibrating 180° out of phase with the central lobe, are less bright. A 180° phase shift in the reference beam modulation inverts the role of the lobes as is shown in Fig. 1(d).

The reference beam modulation for Figs. 1(c) and 1(d) was obtained by sending a narrow reference beam through the same crystal used as the object. Thus any modulation depth and phase that the object can produce can also be used as the reference bias. In fact the entire light distribution of the end face of the crystal has been imaged

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