Proton-irradiation effects on In-Ge:As tunnel junctions*

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The effects of 3-MeV proton irradiation on indium-degenerate germanium (arsenic) tunnel junctions have been studied through measurement of the characteristic curves at 4.2 °K. The acceptor states introduced by the irradiation reduced the net doping in.the semiconductor resulting in increased incremental resistance and reduced semiconductor Fermi level. A calculation of the elastic one-step tunneling conductance which incorporates the doping effects of the irradiation is presented and compared to the data for low levels of irradiation. For high levels of irradiation the characteristic curves are dominated by a large, anomalous, zero-bias, resistance peak which is qualitatively interpreted in terms of impurity assisted, two-step tunneling.

I. INTRODUCTION

Tunneling in metal-semiconductor tunnel junctions has received a lot of attention both theoretically and experimentally. The tunneling current is usually described in terms of two components: one-step elastic tunneling through the Schottky barrier and elastic and inelastic tunneling via assisted processes, such as phonon-assisted tunneling, impurity-assisted tunneling, etc.[1] The theory of the one-step elastic tunneling current has in the case of metal-semiconductor tunnel junctions achieved relatively good quantitative success, particularly in the case of metal-germanium junctions.[2] In the case of assisted processes the phenomena have for the most part been identified, but the calculations of the magnitude have not enjoyed the same success as the unassisted processes.[1–4]

In this paper the effects of proton irradiation of indium-degenerate germanium (arsenic) tunnel junctions will be described. This work was undertaken as a basic study of both of the current mechanisms in tunnel junctions. It is well known that irradiation with particles with energy sufficient to displace atoms leads to defect complexes which usually have energy levels in the semiconductor energy gap.[5] Through these levels the net doping of the barrier region is affected changing the shape of the tunneling barrier and thereby affecting the one-step elastic tunneling current. Also the states associated with the energy levels are states through which impurity-assisted tunneling can flow. Making measurements on irradiated junctions has the important advantage of studying the variation of the effects in the same junction. Indium-germanium (arsenic) junctions were initially chosen as the system to work with because a large amount of work has been done on unirradiated junctions of this type.[2] In addition, a great amount of study has gone into characterizing the effects of irradiation on germanium.[5]

II. EXPERIMENTAL PROCEDURE

The samples used were cut from degenerately doped Ge:As crystals with the long axis being the [111] so that the cleaved face was a (111) plane. Ohmic contacts to one end were made by gold-bonding techniques. The samples were vacuum cleaved in an evaporating stream of metal in a system based on the methods used by Wolf and Compton.[6] Indium was chosen as the metal since preliminary annealing studies indicated that In-Ge junctions were not significantly affected by heating to 120 °C. Contacts to the indium were made using the photoresist techniques of Cullen, Wolf, and Compton.[7]

The incremental resistance (dV/dI) and the second derivative (d^2V/dI^2) were measured at 4.2 °K using standard techniques.[8]

The samples were irradiated with a 3-MeV proton beam in the University of Kentucky's Van de Graaff facility. The beam was collimated to within 40 min. A final collimator with a 4-mm diam hole in it sectioned out a small part of the total beam cross section (1.5 cm in diameter) near the center to obtain a reasonable uniform flux over the junction. The sample was offset 10° with respect to the axis of the beam to avoid channeling effects. The beam impinged on the indium which was on the order of 20 000-Å thick. The temperature of the sample was monitored during irradiation and kept below 60 °C.

III. RESULTS

In Fig. 1 the incremental resistance as a function of voltage for various levels of proton irradiation is shown for a typical sample. Six samples were studied in detail. Many curves were taken for levels of irradiation between those shown in Fig. 1 but the important changes in the characteristic curve are illustrated. These important changes include, for relatively low levels of irra-

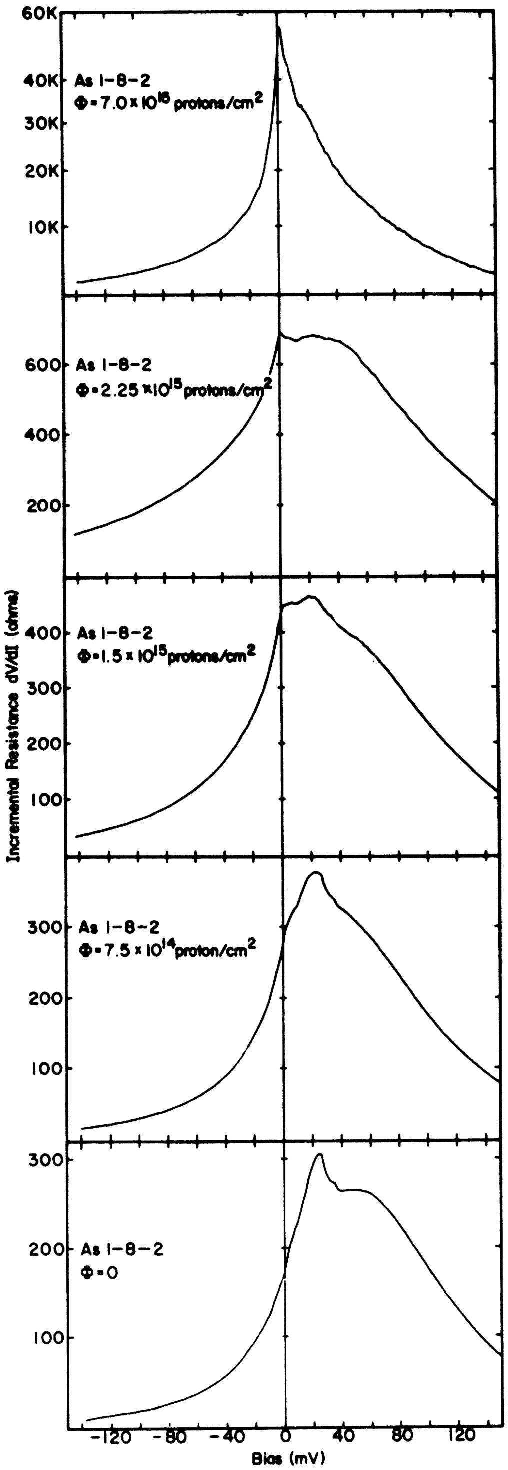

FIG. 1. Incremental resistance vs bias voltage characteristics for sample As 1-8-2 for selected proton dosages. (Note that the vertical scale for the top graph is not linear.)

diation, the increase of resistance and reduction of the Fermi level with increasing irradiation.

The steps in the incremental resistance curves have been identified with phonon-assisted tunneling.[2] If these steps are subtracted out the remaining curve reflects a one-step elastic tunneling character. It has been shown that the peak of this curve occurs at a voltage equal to the Fermi level.[9] It is through this identification that the variation of the Fermi level with irradiation was studied. The increase in zero-bias resistance with irradiation is illustrated in Fig. 2 and the decrease of the Fermi level with irradiation is illustrated in Fig. 3.

At higher levels of irradiation the resistance peak centered about zero bias (zero-bias anomaly) became more prominent and at the highest level of irradiation dominated. It should be noted that in two samples after heavy irradiation, curves similar to low-level irradiation curves, but with greater resistance, were obtained. For the intermediate levels of irradiation for these samples the zero-bias anomaly was growing as usual. It is believed that some of the irradiation defects were annealed out in these samples.

For all samples the curves for the unirradiated case agreed extremely well with previously reported measurements.[2] This justifies describing them as tunnel junctions. In addition, the superconducting test was performed on several samples and a strong superconducting peak was observed in all cases except for samples which had the heaviest irradiation and had extremely large resistance near zero bias associated with the zero-bias anomaly. In this latter case the superconducting test was performed, where the tunneling resistance was the greatest, and it is possible that in this extreme case nontunneling currents such as leakage and capacitive currents were contributing.

IV. ONE-STEP ELASTIC MODEL

The presence of radiation defects will alter the shape of the potential barrier and thus the probability of an electron penetrating it. In this section, a model is developed to account for the changes in the elastic tunneling current due to the changes in the shape of the potential barrier.

For tunneling in which the electron's energy E and its crystal momentum parallel to the junction face $\hbar\vec{k}_{\parallel}$ are conserved, the following expression[1] is normally used to evaluate the current density:

$$J=(2e/h)\int dE[f(E)-f(E+eV)] \times\int\frac{d^2k_{\parallel}}{(2\pi)^2}D(E,\vec{k}_{\parallel}), \qquad (1)$$

$$f(E)=(1+e^{(E-\zeta)/\kappa T})^{-1},$$

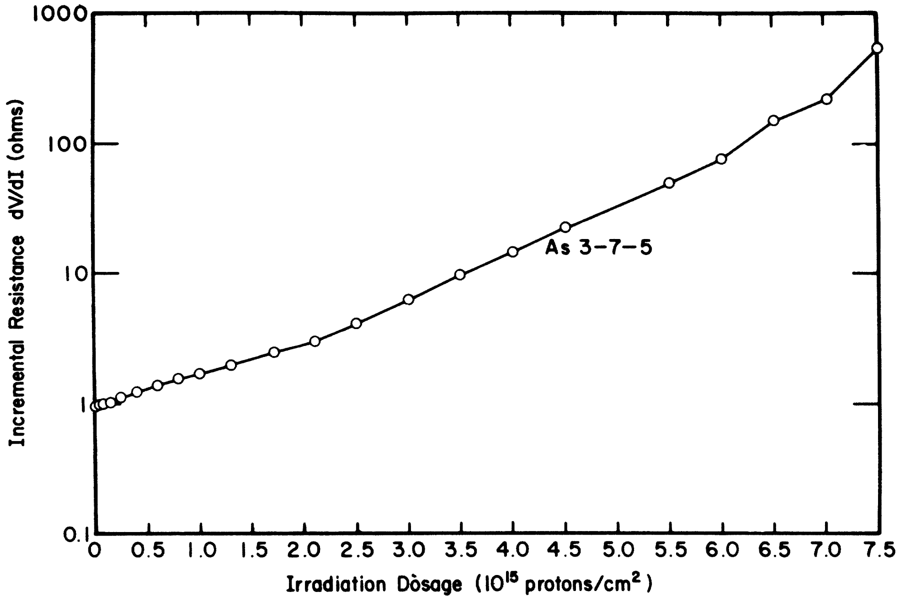

FIG. 2. Incremental resistance at zero bias as a function of proton dosage for sample As 3-7-5.

where e is the charge of electron, h is Planck's constant, V is the bias across the junction, and ζ is the Fermi level of the component of the junction to which the energy is referenced. $D(E, \vec{k}_{\parallel})$ is the barrier penetration factor. $D(E, \vec{k}_{\parallel})$ is evaluated by using a phenomenological description of the barrier. For intimate metal-semiconductor junctions, the common phenomenological model is the "Schottky barrier," where the charge density is assumed to be given by[1]

$$n(x) = eN_D\ , \quad 0 < x < d$$
$$n(x) = 0\ , \quad x < 0,\ d < x \tag{2}$$

where N_D is the donor concentration, and d is the width of the barrier. The barrier is determined by using this charge distribution in Poisson's equation with the boundary conditions

$$V(0) = V_B - eV + \zeta\ ,$$
$$V(d) = 0\ , \tag{3}$$

where the barrier height V_B is experimentally determined.

It is clear that after irradiation Eq. (2) is no longer correct as the acceptors which are filled must be accounted for. It is known[10] that for electron irradiation two acceptor levels are introduced, one at $E_v + 0.26$ eV and another $E_C - 0.20$ eV. The majority of the effects for proton irradiation will be the same as electron irradiation.[5] The primary problem in taking these acceptors into account is that there is no well-defined Fermi level within the barrier region for nonzero biases, due to the nonequilibrium conditions. In this paper, the assumption is made that a quasi-Fermi level can be defined in the barrier region as being the extension of whichever Fermi level is the highest, as illustrated in Fig. 4. This assumption seems plausible because, as Penley[11] showed, the lifetime of the trap is very long and limits the supply function whenever there are electrons available with the energy of the trap level. A similar model was used by Roberts and Crowell[12] in deriving an expression for the capacitance versus bias voltage for a Schottky barrier. The assumption

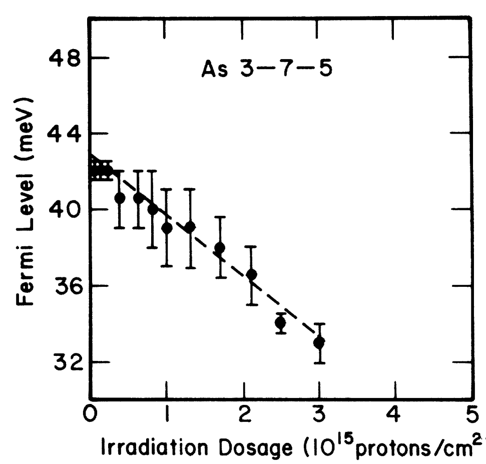

FIG. 3. Value of the Fermi level as a function of proton dosage for sample As 3-7-5. The broken line represents the reduction predicted using a rate of introduction of acceptors as determined from a comparison of the theoretical and experimental increase in zero bias resistance. Only proton dosages for which the zero-bias anomaly was not significant were used.

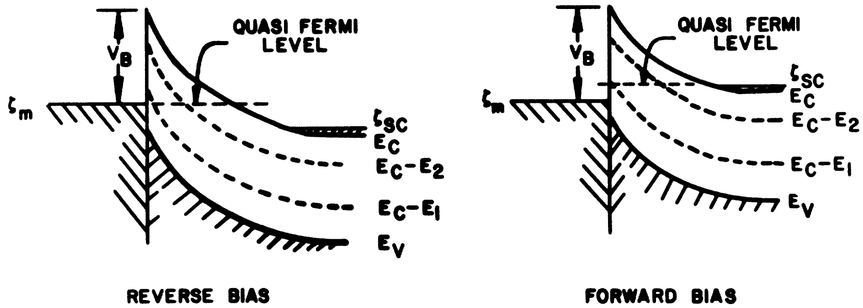

FIG. 4. Potential energy diagram of the barrier showing the acceptor levels and the quasi-Fermi level assumed.

also receives support from a photoelectric study on the interface state density of Pt-Si[13] junctions.

If these assumptions are made then the charge density is (with reference to Fig. 4)

$$n(x) = eN_D, \qquad 0 < x < d_1$$
$$n(x) = e(N_D - N_{A1}), \qquad d_1 < x < d_2 \qquad (4)$$
$$n(x) = e(N_D - N_{A1} - N_{A2}), \qquad d_2 < x < d_3$$

with boundary conditions

$$V(0) = V_B - eV + \zeta,$$
$$V(d_1) = E_1 + \zeta,$$
$$V(d_2) = E_2 + \zeta, \qquad (5)$$
$$V(d_3) = 0,$$

where N_{A1} is the concentration of the impurities with energy levels of $E_C - E_1$ and N_{A2} is the concentration of the impurities with energy levels of $E_C - E_2$.

Solving Poisson's equation for the potential in the barrier region gives

$$V(x) = (N_D e^2/2\epsilon)(x^2 - Ax) + V_B - eV + \zeta, \quad 0 < x < d_1$$
$$V(x) = [(N_D - N_{A1})e^2/2\epsilon](x^2 - Bx + C), \quad d_1 < x < d_2 \qquad (6)$$
$$V(x) = [(N_D - N_{A1} - N_{A2})/2\epsilon]e^2(d_3 - x)^2, \quad d_2 < x < d_3$$

where

$$A = \frac{2(2\epsilon)^{1/2}}{e}\left((E_2+\zeta)\frac{(N_D - N_{A1} - N_{A2})}{N_D^2} + (E_1 - E_2)\frac{(N_D - N_{A1})}{N_D^2} + \frac{(V_B - eV - E_1)}{N_D}\right)^{1/2},$$

$$B = 2\left[d_2 + (E_2+\zeta)^{1/2}\frac{(2\epsilon)^{1/2}}{e}\frac{(N_D - N_{A1} - N_{A2})^{1/2}}{N_D - N_{A1}}\right],$$

$$C = Bd_2 - d_2^2 + \frac{(E_2+\zeta)}{N_D - N_{A1}}\frac{2\epsilon}{e^2}, \qquad (7)$$

$$d_1 = \tfrac{1}{2}A - \frac{(2\epsilon)^{1/2}}{e}\left((E_2+\zeta)\frac{(N_D - N_{A1} - N_{A2})}{N_D^2} + (E_1 - E_2)\frac{(N_D - N_{A1})}{N_D^2}\right)^{1/2},$$

$$d_2 = d_1 - (E_2+\zeta)^{1/2}\frac{(2\epsilon)^{1/2}}{e}\frac{(N_D - N_{A1} - N_{A2})^{1/2}}{N_D - N_{A1}} + \frac{(2\epsilon)^{1/2}}{e}\left((E_2+\zeta)^{1/2}\frac{(N_D - N_{A1} - N_{A2})}{(N_D - N_{A1})^2} + \frac{E_1 - E_2}{N_D - N_{A1}}\right)^{1/2},$$

$$d_3 = d_2 + \frac{(2\epsilon)^{1/2}}{e}\left(\frac{E_2+\zeta}{N_D - N_{A1} - N_{A2}}\right)^{1/2}.$$

A WKB-type analysis similar to the work done by Stratton and Padovoni[14] for unirradiated junctions was carried out to investigate the properties of this model. The WKB barrier-penetration probability was evaluated analytically. This expression was substituted into Eq. (1). The effective mass was assumed constant throughout the junction, therefore the $k_{\parallel}$ integration could be carried out analytically. The remaining energy integral was evaluated numerically on a computer. The resulting current expression was numerically differentiated with respect to voltage to obtain the incremental resistance. When the number of acceptor states was set equal to zero the results were the same as obtained by Stratton and Padovoni.[14]

This theory predicts that there will be an exponential decrease in the elastic tunneling current due to the increasing width of the barrier as acceptor states are introduced. Therefore, the magnitude of the incremental resistance curves should increase. Figure 2 shows the experimental increase in resistance for zero bias and Fig. 5 the theoretical. The absolute value of the theoretical prediction for zero dosage is off by a factor of 20 which is similar to results of Davis and Steinrisser[2] for As-doped units. It should be remembered that other tunneling-current mechanisms are present in the experimental curve after moderate dosages, although their effects are apparently minimal at zero bias.

Another major feature of the model is the reduction of the Fermi level due to the removal of electrons from the conduction band by the acceptors introduced. Figure 3 shows the experimental reduction in the Fermi level for dosages in which elastic one-step tunneling still dominated. From comparison of the theoretical and experimental increase in resistance it is possible to determine the rate of introduction of acceptors assuming each of the two levels are introduced at the same rate. If this rate is used to predict the theoretical reduction in the Fermi level the dotted line in Fig. 3 results. The agreement between theory and experiment here illustrates the consistency of the model.

In addition to the changes noted above, the model predicts some secondary changes in the incremental resistance curves. The exponential character[14] of the far-forward-bias region $eV \gg \zeta$ is retained and the argument increases in value. There is also a steepening of the incremental-resistance curves for $0 < eV < \zeta$. These effects were observed in the samples which annealed leaving the one-step characteristic curves. They were not observed in the one-step elastic curves for low irradiation.

V. ZERO-BIAS ANOMALY

The zero-bias anomaly observed after heavy irradiation in these junctions is similar to many other previously observed[1,15-17] large resistance peaks. These results can be qualitatively interpreted in terms of two-step tunneling,[17] where an electron "hops" from one electrode on to an impurity site, and then "hops" into the other electrode. The transmission probability for this two-step tunneling is greater than that for one-step tunneling and the one-step and two-step tunneling paths act in parallel. At zero bias and low temperature there are few impurity levels within a few kT of the Fermi level and therefore very little two-step tunneling. At zero bias for energies well above the Fermi level there are no electrons to tunnel via the impurity levels and for energies well below the Fermi level there are no vacant states for electrons to tunnel into. As the bias of either sign is increased an increasing number of impurity states can participate in two-step tunneling giving greatly reduced resistance as experimentally observed.

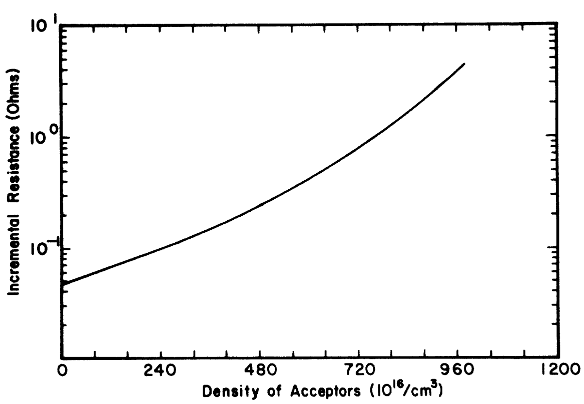

FIG. 5. Theoretical value of the incremental resistance at zero bias as a function of introduced acceptors. The curve was calculated using the model developed in the text and the parameters for As 3-7-5.

The impurity level through which the two-step tunneling is proceeding appears to be associated with the irradiation produced (E_C − 0.20 eV) level. This level is known to anneal[18] near room temperature and for samples which were heated to temperatures only slightly greater than room temperature the zero-bias anomaly disappeared. The $dV/dI-V$ curve then had the one-step tunneling shape with a resistance approximately in agreement with that expected in light of the removal of the (E_C −0.20 eV) acceptors.

As is the case in most large-resistance-peak zero-bias anomalies,[1,15,16] a quantitative theoretical description of the two-step tunneling is not presently possible. A detailed description in terms of Zeller and Giaever's[17] activation energy model cannot proceed because of the lack of knowledge of the energy levels, that is, the energy when the electrons are localized at the impurity site and the energies when they are not. Duke *et al.*[19] have described a theory for resonant-elastic tunneling via impurities which for certain limiting cases can be shown[20] to be identical to the two-step tunneling model described above. One of the requirements for resonant-elastic tunneling is that $T_L = T_R$, where T_L and T_R are the tunneling probabilities from the impurity site to the left and right sides, respectively. The (E_C − 0.20 eV) level approximately satisfies this requirement, however, straightforward application of their theory cannot explain our data. In the theory of Duke *et al.*,[19] when the resonant energy (effectively the impurity energy level) is below one of the Fermi levels, electrons in states with $E > E_r$ (resonance) can tunnel through the resonance giving greater conductance. When the resonance energy is below both Fermi levels the conductance is greater than when it is below only one Fermi level. Resonance energies that are below the zero-bias Fermi level lead to a conductance decrease when bias is applied and they pass above one of the Fermi levels. Resonance energies that are above the zero-bias Fermi level lead to a conductance increase when bias is applied and the resonance energy passes below one of the Fermi levels allowing resonant tunneling to occur. In our Schottky-barrier junction the spatial distribution of the defect complexes leads to an energy distribution of the levels as shown in Fig. 4. The $T_L = T_R$ requirement is not a very sharp one, so available for resonance elastic tunneling there is a distribution of energy levels, including levels both above and below the zero-bias Fermi level. As bias is applied the conductance increase associated with passing one of the Fermi levels above another impurity energy level is offset by the conductance decrease caused by the other Fermi level going below an impurity energy level. Therefore, no large zero-bias anomaly should occur in this model in contrast to what is observed.

In the only other detailed work on irradiated metal-semiconductor tunnel junctions[15] and in a work on low-doped metal-semiconductor tunnel junctions[16] the large resistance peak was interpreted as associated with the Mott transition in the semiconductor. In the Hubbard[21] picture of the Mott transition, a gap in the density of states opens up near the Fermi level when the concentration is reduced below a critical value. This of course would lead to a large resistance peak about zero bias as no states for low bias would be available for tunneling into or out of. The introduction of acceptor states through proton irradiation would lower the net doping and therefore be expected to lead to a metal-insulator transition. However, we do not believe that this is the explanation for our data because to reduce the carrier concentration in the semiconductor to $n_c = 3\times10^{17}$ cm^{-3} the space-charge density over large portions of the barrier would be reduced to such a low level that the barrier width [see Eq. (7)] would be so great that essentially no tunneling would occur. In other materials such as silicon, the Mott transition occurs at higher concentrations, for example, 5×10^{18} cm^{-3} in Si : B,[16] giving a thinner tunneling barrier at the Mott transition.

For the reasons cited about, the zero-bias anomalies are qualitatively interpreted as due to two-step tunneling. Further theoretical and experimental work is in progress in an attempt to obtain a quantitative theoretical description of this zero-bias anomaly.

VI. SUMMARY

In summary, the effects of proton irradiation on indium-degenerate germanium (arsenic) tunnel junctions have been described. The primary effect of the irradiation was to introduce acceptor states which lowered the net doping in the semiconductor and introduced additional energy levels in the tunneling barrier. For lightly irradiated junctions one-step tunneling dominated and the dependence of net doping density in the junction region and variation of the Fermi level in the near semiconductor were studied as a function of radiation. For moderately irradiated junctions two-step tunneling via impurities entered and for heavily irradiated junctions two-step tunneling dominated. Andrews *et al.*[3] have pointed out the following for *p-n* or metal-semiconductor tunnel junctions: For high doping the tunneling current can be described by the one-step elastic current; at lower doping, impurity-assisted processes become more prominent; and finally, for very low doping, effects associated with the metal-insulator transition appear. In our junctions the effect of irradiation was to lower the net doping. We do not believe our samples were irradiated sufficiently to undergo the Mott transition; however, the first and second part of this sequence are clearly illustrated. It is significant that this was being observed in the same junction where the doping was lowered through irradiation and uncontrollable variations associated with different samples were entirely avoided.

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