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Zero-Bias Anomaly in Irradiated Pb-GaAs Tunnel Junctions, and the Mott Transition*

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Pb-GaAs Schottky barriers irradiated progressively by 10-MeV electrons or fast neutrons were found to exhibit anomalous behavior identical to that produced by varying the initial doping. The results are consistent with the Hubbard model of the Mott transition.

In a recent Letter, Wolf, Losee, Cullen, and Compton[1] have reported the observation of an anomalous zero-bias resistance peak in Schottky-barrier tunnel junctions on Si:B which appears as the semiconductor impurity concentration approaches the critical Mott concentration N_c.[2,3] They suggest that the peak is due to a gap or sharp minimum, at the Fermi energy, in the density of states in the semiconductor, in accord with the Hubbard[4] model of the Mott transition. Here, we present results of an extensive study, carried out independently of the above authors' work, of the effect of high-energy (10-MeV) electron and fast-neutron bombardment on the zero-bias anomaly in p-GaAs-Pb Schottky-barrier tunnel junctions. Our results strongly suggest that the zero-bias anomaly can indeed be explained in terms of the Hubbard-Mott model for the impurity band in heavily doped semiconductors. They show that the changes in the anomaly produced by the irradiation result solely from the reduction of the free carrier concentration through trapping of carriers by defect states introduced into the GaAs by the irradiation. The obvious advantage of these irradiation experiments is that one can study the effect on the anomaly of a change in carrier concentration in the *same* junction. An explanation of the anomaly in terms of two-step tunneling through real intermediate states in the barrier[5,6] is possible although not as likely as one involving the Mott transition, as will be shown below and in more detail in a later publication.[7]

The junctions were prepared by the vacuum deposition of Pb onto p-GaAs single-crystal wafers that were chemomechanically polished in a dilute solution of Br (0.05–0.1% by volume) in methanol. Typically, seven junctions were made on a single wafer using Kodak Thin Film Resist to define the junction area (approximately 1.2×10^{-4} cm^2). Samples with selected carrier concentrations were irradiated with progressively increasing doses of 10-MeV electron pulses or by fast reactor neutrons.

Prior to irradiation, highly doped junctions ($p \geq 8\times10^{18}$ cm^{-3}) showed a good Pb superconducting gap, a well-resolved Pb phonon density of states, and the GaAs LO-phonon structure at +36 mV, thus showing them to be good tunnel junctions.[7] The zero-bias anomaly appeared as a resistance peak with a magnitude at $T \leq 4.2$°K of ~15% relative to the extrapolated background R_b, with a half-width of ~12 mV, as evident from Fig. 1(a). The smaller and narrower (~1%, half-width 1 mV) resistance dip superimposed upon the broader resistance peak [Fig. 1(a)] was attributable to tunneling with spin-flip via localized magnetic states in the barrier.[8,9]

The effect of both electron and neutron irradiations on the tunneling characteristics was essentially the same. Progressively larger doses of radiation increased the relative size of the re-

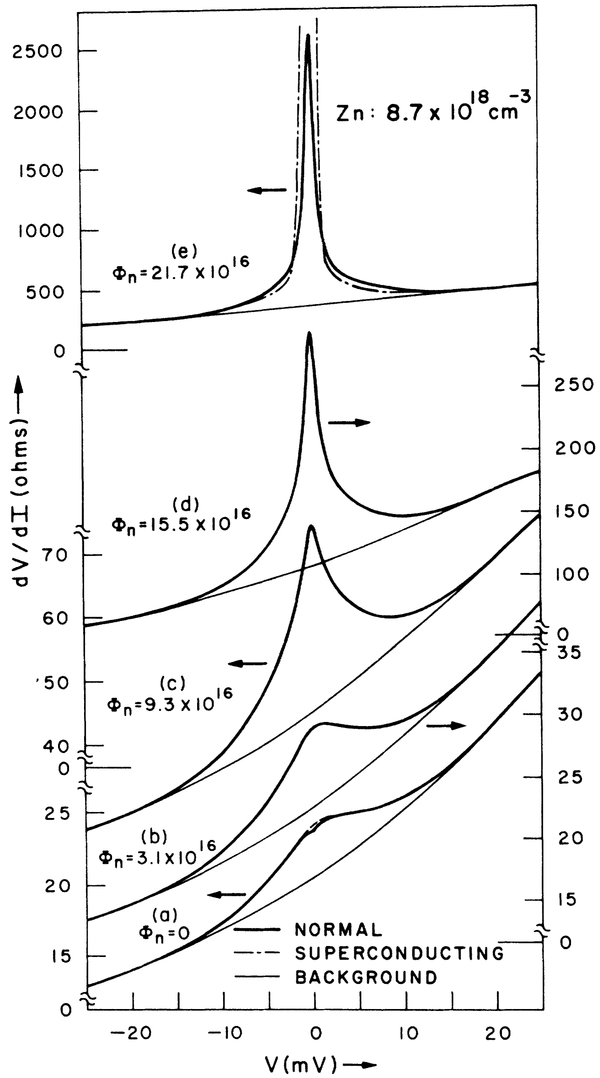
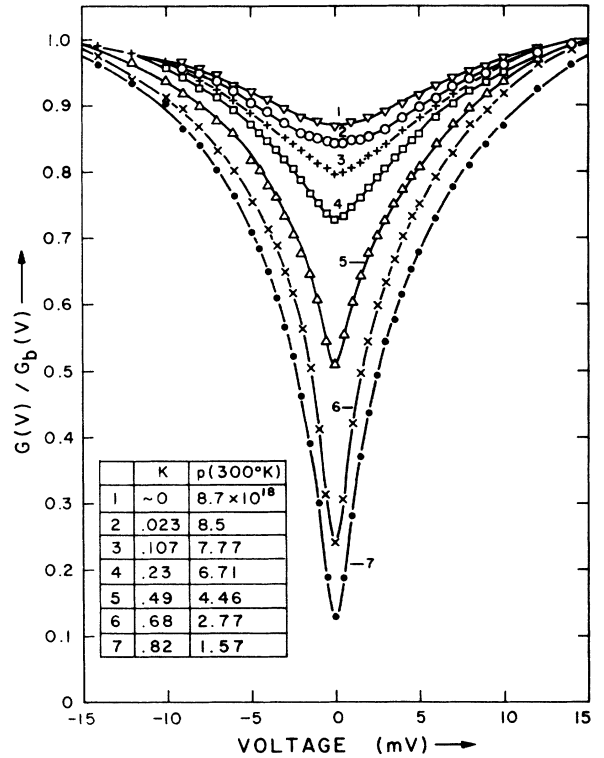


FIG. 1. Voltage dependence of the differential resistance at 1.42°K for junction 8A-4 subjected to successive neutron doses Φ_n (n/cm^2): (a) p(300°K) $=8.7\times10^{18}$; (b) $p=7.7\times10^{18}$; (c) $p=5.57\times10^{18}$; (d) $p=3.57\times10^{18}$; (e) $p=2.13\times10^{18}$ cm^{-3}.



	K	p(300°K)
1	~0	8.7×10^{18}
2	.023	8.5
3	.107	7.77
4	.23	6.71
5	.49	4.46
6	.68	2.77
7	.82	1.57

FIG. 2. Voltage dependence of the normalized conductance $G(V)/G_b(V)$ at 1.42°K for junction 8B-4 after successive neutron irradiations. The integrated neutron flux is (1) 0; (2) 0.6; (3) 2.8; (4) 5.9; (5) 12.1; (6) 18.3; (7) 24.5, all in units of 10^{16} n/cm^2.

sistance peak $[R(0)-R_b(0)]/R_b(0)$ from ~15 to ~600% at 1.4°K with an accompanying increase in the background resistance $R_b(0)$ of about 20 [Figs. 1(b)–1(e)]. The resistance dip disappeared after a moderate exposure to irradiation. Moreover, below 4.2°K the anomaly in heavily irradiated junctions became strongly temperature dependent in contrast to its temperature independence prior to the irradiation. In this range the zero-bias conductance $G(0)$ $(G\equiv dI/dV)$ of heavily irradiated junctions showed an approximately linear dependence on temperature. The irradiation also caused distortion and smearing of the Pb superconducting characteristics as shown in Fig. 1(e) for the most heavily irradiated junctions.

Figure 2 shows the change of the normalized conductance $G(V)/G_b(V)$ at 1.42°K for junction 8B-4 ($p_0=8.7\times10^{18}$ cm^{-3}, Zn doped) which was the most heavily neutron-irradiated sample. It is well known[10] that high-energy radiation produces a random distribution of defects in GaAs whose energy levels are distributed in the energy gap. These defects act to trap the free carriers, thereby reducing their density. The change in the free-carrier concentration caused by the neutron irradiation was determined from Hall-effect measurements on irradiated (Hall) samples cut from the same wafers used for fabricating the junctions. The deduced room-temperature carrier concentration p (which measures the net low-temperature un-ionized acceptor concentration) and the degree of compensation $K=\Delta p/p_0$ produced by irradiation are indicated in Fig. 2.

Large variations in the zero-bias anomaly were also produced by varying the initial doping of the GaAs crystal. The normalized conductance plots are essentially similar to those shown in Fig. 2. The normalized zero-bias conductance $G(0)/G_b(0)$ decreases from 0.9 to 0.025 as the carrier concentration is reduced from $\sim 1\times 10^{19}$ cm^{-3} to 8.8×10^{17} cm^{-3}, as shown in Fig. 3(a) for various junctions. Note that sample 2A is Cd-doped whereas all other samples are Zn doped. In Fig. 3(a) [and in Fig. 3(b) below] repetition of a given set of symbols at succeedingly lower concentrations represents the effect of the progressive neutron irradiation of that sample, the set at the highest concentration in a series always denoting an unirradiated sample. The different points at the same concentration represent the scatter of the data taken on different junctions on the same chip. It is evident from Fig. 3(a) that the main factor determining the size of the anomaly is the carrier concentration in the *bulk* GaAs, irrespective of whether that concentration was obtained by initial doping with acceptor impurities, or reduced to the same value from an initially higher level through the effect of compensation produced by the irradiation. This behavior rules out the direct participation of the defect states introduced by the irradiation (up to $\sim 7\times 10^{18}$ cm^{-3}) in a two-step tunneling process.[5,6,11,12] In order to attribute the anomaly to some other two-step process (excluding the approximate "two-step" interpretation of the Hubbard model by Wolf *et al.*[1]) one has to assume that the appropriate set of states involved has approximately the same density and distribution in GaAs samples with widely different defect and acceptor concentrations. This does not seem likely. Additional evidence against the two-step models will be discussed in detail elsewhere.[7] Here, we only discuss the following two major experimental observations. (1) The zero-bias conductance in unirradiated junctions with $p = 2.13\times 10^{18}$ cm^{-3} decreases in high magnetic fields ($H > 20$ kG) reaching 25% by 80 kG, while the line shape remains essentially unchanged. (2) The dependence of the conductance linewidth on the carrier concentration undergoes a functional change near 2×10^{18} cm^{-3} as shown in Fig. 3(b) for various samples with different preirradiation carrier concentrations. The linewidth decreases from ~ 12 mV at $p \gtrsim 8.7\times 10^{18}$ cm^{-3} to ~ 5 mV around $p = 2\times 10^{18}$ cm^{-3} ($T = 1.4$°K), then starts to increase again as the carrier concentration is reduced further. Similarly, the decrease in $G(0)/G_b(0)$ as a function of the carrier concentration [Fig. 3(a)] is particularly rapid in the vicinity of 2×10^{18} cm^{-3}. It should be noted that the value $p = 2\times 10^{18}$ cm^{-3} is near the theoretical Mott concentration[2,3] N_c which is $\sim 1\times 10^{18}$ cm^{-3} in GaAs. Experimentally, the Hall mobility μ_H and conductivity at 1.4°K showed a strong dependence on the room-temperature carrier concentration p in the vicinity of $p = 2\times 10^{18}$ cm^{-3}. Also, the dependence of the resistivity on $1/T$ exhibited a nonvanishing activation energy at temperatures below 10°K

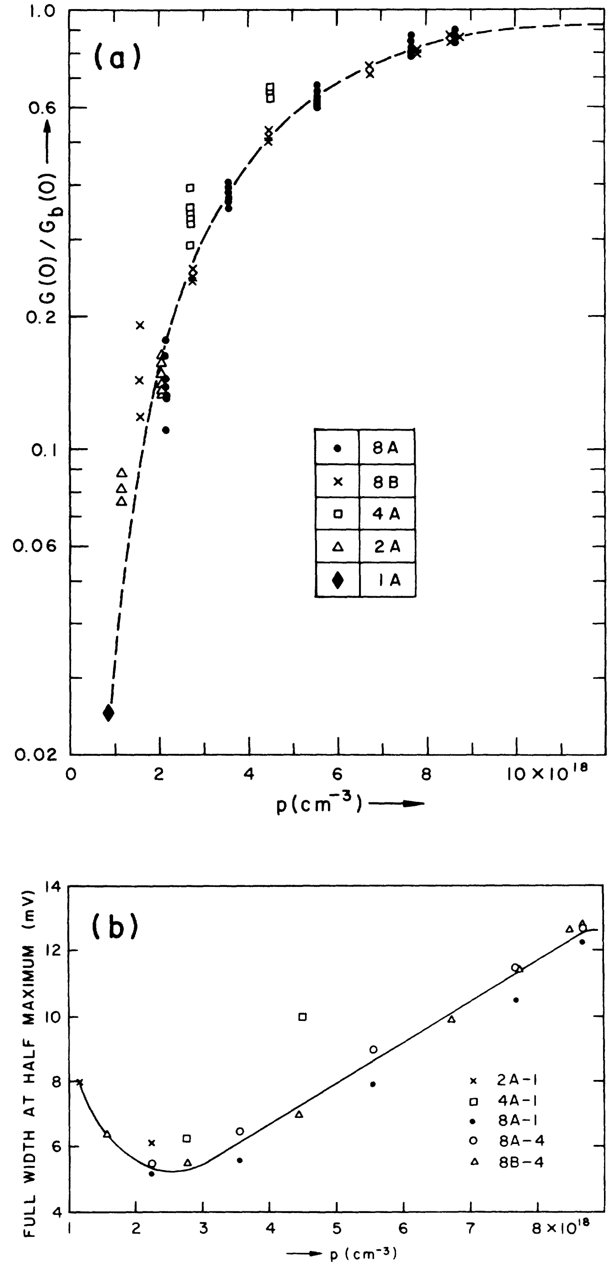


FIG. 3. Dependence at 1.42°K of (a) the normalized zero-bias conductance $G(0)/G_b(0)$ and (b) the conductance linewidth on the room-temperature carrier concentration of various neutron-irradiated and differently doped samples.

only when $p<2\times10^{18}$ cm^{-3}. Therefore, a Mott transition is expected to occur in p-GaAs near $N_c \sim 2\times10^{18}$ cm^{-3}.

The aforementioned tunneling data can be satisfactorily explained in terms of a sharp minimum in the density of states at the Fermi energy near N_c assuming that in this range the conductance is related to the density of states. According to the Hubbard model,[4] this minimum, in the immediate vicinity of which the states are partially localized, is a result of the Coulomb interaction between carriers of antiparallel spin on the same site. As p increases above N_c, this minimum is smeared out and hence the conductance line shape is also smeared and broadened. As p decreases below N_c, however, the minimum develops into a gap; hence, the conductance halfwidth increases and the zero-bias conductance decreases very rapidly in this range. This model also explains[7] (a) the strong temperature dependence of the zero-bias conductance of junctions with p near N_c; (b) the observed conductance decrease in high magnetic fields as caused by the freezeout of carriers in high fields[13]; and (c) the smearing of the Pb superconducting characteristics[14] due to the broadening of the final states in the semiconductor as suggested by Wolf *et al.*[1]

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[14] The smearing of the superconducting characteristics may also be evidence of the opening up of conductance channels not involving tunneling, or at least not direct elastic tunneling. The absence in our junctions of a parallel upward voltage shift in the superconducting I-V characteristics relative to the normal characteristics, as expected for two-step tunneling (see Ref. 6), argues against that particular mechanism, however.

Propagation of Heat Pulses in p-Type Germanium under Uniaxial Stress*

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Absorption of phonons by stress-split acceptor states in germanium has been observed. A distinction is found between the "static" ($a^*q \ll 1$) and "dynamic" ($a^*q \gtrsim 1$) deformation potential constant (a^* is the effective Bohr radius of impurity; q is the wave number of relevant wave component), thus resolving an apparent conflict in previous reports. The effect of phonon scattering by isotopic impurities and of resonant phonon absorption results in phonon propagation in a well-defined frequency interval (phonon "window").

The ground state of shallow acceptors in Ge (and in Si) is fourfold degenerate.[1] The application of uniaxial stress leads to the splitting of these states into two (Kramers) doublets. When the stress is applied along threefold or fourfold symmetry axes, the doublets can be specified by the quantum numbers $M_J=\pm\frac{3}{2}$ and $M_J=\pm\frac{1}{2}$. The present experiment is designed to study