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Disorder effects in reduced dimension: Indium–phosphide-based resonant tunneling diodes

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Disorder alters the current–voltage characteristics of low-dimensional devices such as resonant tunneling diodes (RTDs) differently than conventional electronic devices, because of the increasing importance of quantum effects. There are now enough experimental data, including new measurements presented here, for the basis of a detailed model of radiation effects in RTDs to be developed. A model is presented in which the reduced dimensionality in the density of states of RTDs renders scattering of charge carriers from atomic defects highly effective in removing the carriers from resonance. © *2000 American Institute of Physics.* [S0021-8979(00)06724-4]

Continuing advances in miniaturization have pushed the size of advanced electronic devices into the region where quantum effects become dominant. In devices such as resonant tunneling diodes (RTDs) and high electron mobility transistors (HEMTs), for example, the traditional carrier transport mechanisms of drift and diffusion, are replaced by quantum tunneling or ballistic transport. An important result of the miniaturization is that the functional dimensionality of the devices is reduced: Carrier transport in HEMTs is effected by electrons moving in a quasi two-dimensional gas; and in RTDs, the electron density of states is compressed into two dimensions in momentum space.

Decreasing the size and dimensionality of a device affects more than the physics of its operation. As the number of atoms involved in device functionality is reduced, the influence of atomic-scale disorder increases. In a carbon nanotube, for instance, one displaced atom can mean the difference between a semiconducting and a metallic state.[1] In order to design novel reduced-dimensional and quantum electronic devices that are resilient and robust with respect to disorder, it is necessary to understand how displaced atoms affect device performance.

In this communication, we use current and published data[2–4] to establish three empirical rules for the tunneling current in irradiated InP-based RTDs, and then develop a theory to explain the present results and to make predictions for other types of RTDs.

In an RTD, an emitter and collector are separated by two tunneling barriers and a quantum well. We take the x axis to be perpendicular to the barrier faces, so that tunneling occurs in the x direction. The energy distributions of carriers in the emitter and collector are three-dimensional Fermi distributions, but inside the well, momentum conservation restricts the x component of momentum, causing the density of states to be compressed into two dimensions. The reduced-dimensional aspect of resonant tunneling can be further illustrated by a k-space diagram, in which tunneling is limited to a resonance disk of width δk_x located at $k_x = k_{x,\mathrm{res}}$.[5]

As discussed elsewhere,[6,7] the RTDs used here are based on direct-tunneling AlAs/InGaAs/InAs/InGaAs/AlAs structures (2/2/2/2/2 nm) whose cross-sectional areas varied from 0.3×0.3 to $1\times1\ \mu\mathrm{m}^2$. Average peak currents varied between about 4 and about 97 μA. For testing purposes, devices were wired into arrays containing 100 or 1000 RTDs in parallel.

Irradiations were performed at 300 K in a tandem Van de Graaf accelerator, using incremental fluences Φ of 3 MeVH^+, 3 MeVHe^+, and 12.5 MeVSi^{4+}ions incident at 7° from the surface normal to discourage ion channeling effects. The average range of the different ions in the structures varied from about 6 μm for Si^{4+} to about 60 μm for H^+. All ions passed through the RTDs without significant energy loss, and stopped in the InP substrates. As calculated using the Monte Carlo program SRIM,[8] the maximum fluences used (7×10^{14}, 4×10^{13}, and 2.4×10^{11} ions/cm^2) correspond to initial radiation-induced defect concentrations of 1.5×10^{-4}, 1.7×10^{-4}, and 9×10^{-5} displacements per target material atom (dpa) for the H^+, He^+, and Si^{4+}ions, respectively.

For the devices, fluences, and ions described here, irradiation creates mainly point defects whose concentration c is[9,10]

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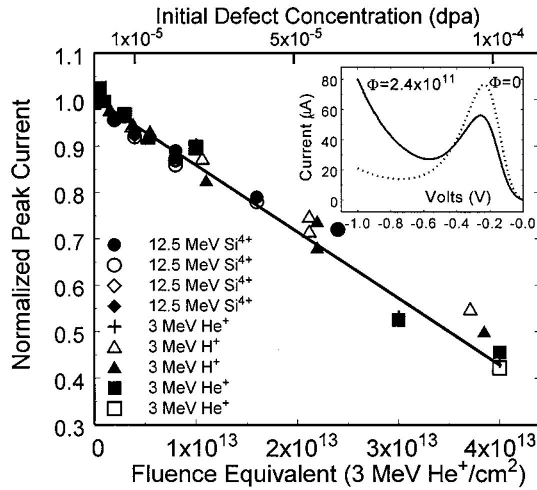

FIG. 1. Normalized peak current vs fluence and approximate initial defect concentration for 12 arrays of InP-based RTDs. The peak current decreases linearly with defect concentration for all arrays. (Inset) Current–voltage curves for one array before and after irradiation to a fluence of 2.4×10^{11} 12.5 MeV Si^{4+} ions/cm^2.

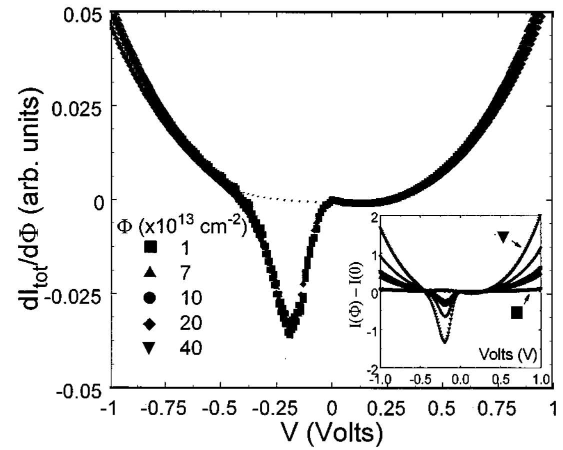

FIG. 2. (Inset) Difference curves obtained from subtracting postirradiation current–voltage curves from preirradiation curve. (Main figure) Fluence-normalized difference curves, $dI_{\rm tot}/d\Phi$. Note sharp radiation-induced decrease in current around resonance near -0.2 V. Dashed line represents Eq. (3).

$$c=D\Phi, \tag{1}$$

where D is a damage factor specific to the incident particle mass and energy, and to the target material. The parameter D also depends on details of the material and the irradiation, including postirradiation recombination and annealing. For the present discussion, however, D can be taken as constant for each incident ion and ion energy.

Each array displayed typical ''n-shaped'' current–voltage curves at room temperature. From each curve, the currents and voltages at the transmission peak and valley, I_p, V_p, I_v, and V_v, were determined. Initial defect concentrations below about 5×10^{-6} dpa did not noticeably affect the RTDs.

As can be seen in the inset of Fig. 1, radiation damage decreased the peak current while increasing the valley current. In the main body of the figure, the normalized peak current $I_p(\Phi)/I_p(0)$ can be seen to decrease linearly with fluence for all 12 arrays. The first empirical rule is then

$$I_p(\Phi)/I_p(0)=1-\alpha(\Phi/7.14\times10^{13}\text{cm}^{-2}), \tag{2}$$

where the scaling factor α is 0.052, 1, and 87 for 3 MeV H^+, 3 MeV He^+, and 12.5 MeV Si^{4+}, respectively. The different values of α imply that 3 MeV He^+ ions are 20 times more damaging than 3 MeV H^+, but 87 times less damaging than 12.5 MeV Si^{4+}.

In any RTD, the measured current $I_{\rm tot}(V,\Phi)$ is the sum of the resonance current $I_{\rm res}(V,\Phi)$, and the current passing through the device via sequential, nonresonance, or leakage channels, $I_{\rm non}(V,\Phi)$. In practice, it is difficult to separate the relative contributions of $I_{\rm res}$ and $I_{\rm non}$ from $I_{\rm tot}$. However, the quantity of most physical interest here is not $I_{\rm res}$ but $dI_{\rm res}/d\Phi$, which reveals how the tunneling current is perturbed by radiation-induced disorder. Fortunately, $dI_{\rm res}/d\Phi$ can be extracted from the data.

Difference curves $I_{\rm tot}(\Phi)$–$I_{\rm tot}(0)$ are shown in the inset of Fig. 2 for an array irradiated with protons. Values of $dI_{\rm tot}/d\Phi$ are shown in the main body of the figure. Near the resonance (at $V\approx-0.2$ V), radiation damage suppresses $dI_{\rm tot}/d\Phi$ in such a way that the line shape of the suppressed region remains constant. (This is the second rule.) Far from resonance, however, radiation damage generally increases the current. Data for other arrays reveal the same trends.[4] The off-resonance component of $dI_{\rm tot}/d\Phi$ follows a cubic relationship. That is,

$$dI_{\rm non}/d\Phi=0.05\,V^3. \tag{3}$$

Extrapolating Eq. (3) to V_p reveals that $|dI_{\rm non}/d\Phi|$ is negligible compared to $|dI_{\rm tot}/d\Phi|_{v=v_p}$. Hence, the third empirical rule is that $dI_{\rm tot}/d\Phi\approx dI_{\rm res}/d\Phi$ for V near V_p.

We now consider the implications of the above results. First, since $|dI_{\rm non}/d\Phi|\ll|dI_{\rm res}/d\Phi|$, radiation-induced increases in leakage current through the substrate or quantum barriers can be neglected at $V=V_p$. In fact, *all* radiation-induced changes that affect only $I_{\rm non}$ can be ignored here. Second, the fixed shape of $dI_{\rm res}/d\Phi$ means that the parameters determining the resonance shape are also effectively constant. These parameters include the incident longitudinal velocity, the carrier effective mass, and the heterostructure dimensions.[5] The same parameters, plus the Fermi and resonance energies, determine the magnitude of $I_{\rm res}$. None of these parameters are expected to change at the small defect concentrations considered here.[11]

Viewed from the perspective of quantum mechanics, the resonance current is actually an eigenvalue of a tunneling-interaction operator acting on the eigenfunction of an RTD. Since the eigenfunction is determined by physical and solid-state parameters, and since these parameters are constant (see above), the eigenfunction must be constant too. Therefore, the observed radiation-induced decrease in $I_{\rm res}$ must be due to a change in the tunneling interaction. Resonant tunneling derives from the application of energy and momentum conservation to electrons incident at the barriers. Therefore, in order for the interaction to be perturbed, either energy or

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momentum must no longer be conserved. Since the scattering potential is conservative,[12] it is likely that momentum conservation is being broken.

In general, scattering of an electron from a defect alters its momentum in three dimensions without changing its energy. Outside the quantum well, where there are no dimensional constraints on momentum, scattering affects the transport current only by altering the carrier mobility. Inside (or very near) the well, however, where the electron wave function is two dimensional, defect scattering can easily deflect an electron from the resonance state, leaving it to make its way out of the well by means of sequential tunneling.[13,14] The only two mechanisms that meet the above conditions are scattering of tunneling electrons from radiation-induced defects inside the well or from radiation-roughened interfaces bordering the quantum well.

Recent numerical simulations suggest that the amount of interface roughening likely to occur at the low defect concentrations considered here is probably too small to significantly reduce I_p.[15–17] Hence, we assume that interface roughening is presently a small perturbation on the main effect of scattering from radiation-induced defects inside the well. Let us now calculate the effect of such scattering on I_{res}.

The probability P_s that a carrier inside the well scatters from a radiation-induced defect is, from Eq. (1) and Refs. 8 and 9,

$$P_s = \beta c = \beta D \Phi, \tag{4}$$

where β depends on scattering cross sections and impact parameters. If all carriers scattered by radiation-induced defects inside the well are removed from the resonance current, and if no carriers are scattered back in, then

$$I_{res}(\Phi) = I_{res}(0)[1 - P_s] = I_{res}(0)[1 - \beta D \Phi], \tag{5}$$

where $(1 - P_s)$ is the probability of *not* scattering from a radiation-induced defect in the well.

Due to the nonzero resonance width δk_x, there is a small probability p_r that scattering does not remove a carrier from resonance. For isotropic scattering, $p_r = \delta k_x / 2\pi k_f$ (see Refs. 5 and 14). More generally, $p_r = \zeta \delta k_x / 2\pi k_f$, where the anisotropicity factor $\zeta = 1$ for an isotropic potential; $\zeta < 1$ for potentials that preferentially scatter away from the k_x direction, and so on.

We define the rescattering parameter γ as the probability that a carrier previously scattered out of resonance in the well scatters *again* before leaving via sequential tunneling. Like P_s, γ is a function of scattering impact parameters and the defect concentration, but unlike P_s, γ is also a function of the barrier transparency.[16,17] For highly opaque barriers, $\gamma \to 1$.

To improve upon Eq. (5), we must compensate for the effects of scattering and rescattering inside the well. One way to do so is to calculate the probability that an electron, which scatters *i* times inside the well, ends up in the sequential tunneling current, then summing over all *i*, and subtracting the result from unity. The result is an exact expression for I_{res}

$$\frac{I_{res}(\Phi)}{I_{res}(0)} = 1 - P_s \left[\frac{(1-p_r)(1-\gamma)}{1-\gamma(1-p_r) - p_r P_s} \right]. \tag{6}$$

Equation (6) is linear in P_s and Φ for narrow resonances (small P_r), for transparent barriers (small γ), and in the limit that $P_s \ll [1-\gamma(1-p_r)]/p_r$. As p_r or $\gamma \to 1, I_{res}(\Phi)/I_{res}(0) \to 1$, as expected. In linear form, Eq. (6) describes all data on the peak current presented above, and in Refs. 2–4.

The strong tendency of Eq. (6) toward linearity in P_s makes it tempting to predict that I_p should decrease linearly with fluence in all irradiated tunneling diodes. However, Eq. (6) can lose its applicability if the interface roughness increases significantly with irradiation, if the device eigenfunction is changed by irradiation, or if the initial conservation laws are different—as might be the case for interband tunneling diodes.

In summary, we find that the linear decrease of I_p in irradiated InP-based RTDs is the result of three-dimensional (3D) scattering in a two-dimensional quantum well. This effect arises from the reduced dimensionality in the RTDs, and does not occur in ''conventional'' (3D) devices. Comparable effects have been observed in just one other system. Radiation-induced defects on the Cu–O planes in high temperature superconductors are known to scatter Cooper pairs away from the planes with high efficiency, thereby causing a strong depairing-like reduction in the transition temperature.[18]

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