MeV ion-induced suppression of resonance current in InP-based resonant tunneling diodes

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We present the results of an experiment on 12.5 MeV Si^{4+} ion-irradiated InP-based resonant tunneling diodes. Radiation damage suppresses the entire resonance in direct proportion to the ion fluence. The suppression is not caused by a change in the tunneling barrier heights or widths, as previously thought; nor is it caused by radiation-induced increases in the leakage current. In fact, none of the internal parameters such as the Fermi energy and the resonant energy of the quantum well are expected to be greatly altered by the irradiation. We propose that radiation-induced disorder decreases the resonance current by scattering carriers out of the reduced-dimensional region of k space in which tunneling is allowed.
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Disorder plays an important role in semiconductor electronics. Its presence in the form of dopants is often necessary for proper device function, but at other times its presence is harmful. In either case, it is important to study how electronic devices respond to disorder. For established technologies such as silicon-based minority carrier devices, there is a vast body of information on disorder effects, but for new and emerging technologies such as resonant tunneling diodes (RTDs), there is not.

Because of their fast switching times and tunable negative differential resistance, InP-based RTDs show great potential for a variety of applications. They are the fastest semiconductor switching devices, with demonstrated large signal switching speeds as high as 300 mV/ps and switching times as short as 1.5 ps.[1] These devices can significantly enhance circuit performance and are now being developed for use in systems with 10–100 GHz data rates.[2]

Particle irradiation is an effective method for creating controlled amounts and types of disorder in materials. Only two studies have been presented so far on irradiated RTDs—the first using 3 MeV protons, and the second using 3 MeV helium ions.[3,4] Here, we present the results of 12.5 MeV Si^{4+} ion irradiation experiments on InP-based RTDs.

Films were grown by molecular beam epitaxy. The RTDs are based on an AlAs/InGaAs/InAs/InGaAs/AlAs structure (2/2/2/2/2 nm) with InAlAs used to reduce the tunnel current density, similar to structures previously described.[5] Each device has an n^+InGaAs contact layer above and below the RTD structure. Four arrays of devices were tested. The first array consisted of one hundred $1\times1\ \mu$m RTDs in parallel. The second contained one-thousand $0.3\times0.3\ \mu$m RTDs in parallel. The third and fourth contained one hundred $0.5\times0.5\ \mu$m devices in parallel.

Current–voltage ($I-V$) curves were measured using a HP 4155 semiconductor parameter analyzer. The RTD arrays displayed n-shaped curves typical of these bistable devices. Five variables were determined from each $I-V$ curve. These are I_p and V_p, the current and voltage at the tunneling transmission peak, I_v and V_v, the current and voltage at the transmission minimum, and I_p/I_v, the peak-to-valley current ratio.

Irradiations were performed at room temperature in a tandem Van de Graaf accelerator, using 12.5 MeV silicon ions incident 7° from the surface normal to discourage ion channeling effects. Silicon ions of this energy have a range of about 6 μm in InP, and so traverse the RTDs without significant energy loss. Disorder caused by 12.5 MeV Si^{4+} consists mostly of point defects such as vacancies and interstitials, and also some larger defect clusters. In a typical experiment, the $I-V$ curve of an array was measured, the array was irradiated with an incremental fluence Φ, and the procedure was repeated.

$I-V$ curves for one array are shown in the inset of Fig. 1 before and after irradiation to a fluence of $2.4\times10^{11} 12.5\ \mathrm{MeV\ Si}^{4+}/\mathrm{cm}^2$. As can be seen in the figure, radiation damage decreases the peak current and increases the valley current, while shifting the peak and valley closer together. The same trends are observed for all four arrays described here, and for similar arrays irradiated with protons and helium ions.[3,4]

The effect of Si^{4+} irradiation on the normalized valley current $I_v(\Phi)/I_v(0)$ is shown in the main body of Fig. 1. The valley current increases with fluence, but the rate of increase differs among the arrays. Similar results have been observed in other irradiated RTD arrays.[3,4] Although the valley current is an important operating parameter in RTDs, it is

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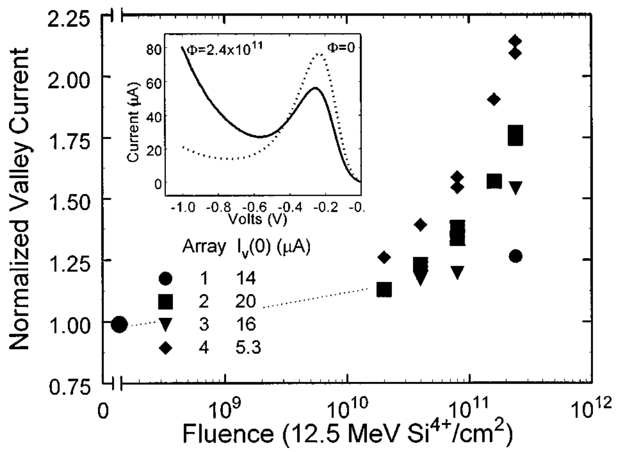

FIG. 1. Normalized valley current $I_v(\Phi)/I_v(0)$ for four RTD arrays vs 12.5 MeV Si^{4+} ion fluence. Values of $I_v(0)$ are given in the legend. The dashed line serves to guide the eye. Inset: $I-V$ curves for one array before and after irradiation to a fluence of $\Phi=2.4\times10^{11}$ ions/cm^2.

not an intrinsic parameter, and hence, is difficult to study analytically. Modeling and computer simulations show that valley currents depend strongly on initial defect concentrations and numerous other nonideal effects[6] that are unknown for these specific arrays. Therefore, a detailed analysis of the valley current is not undertaken here.

The normalized peak current is shown plotted versus fluence in Fig. 2. To within 3% uncertainty, the peak current decreases linearly with fluence, at the same rate for all four arrays; that is

$$I_p(\Phi)/I_p(0)=0.986-(1.19\times10^{-12}\text{cm}^2)\Phi. \tag{1}$$

Equation (1) is depicted as the solid line in Fig. 2. The peak current decreases linearly for proton and helium ion irradiations as well.[3,4]

The normalized peak-to-valley current ratio I_p/I_v is shown in the inset of Fig. 2. As can be seen, I_p/I_v decreases with fluence, but not in the simple, uniform, linear way that the peak current decreases. We attribute this difference to the influence of the less-predictable I_v.

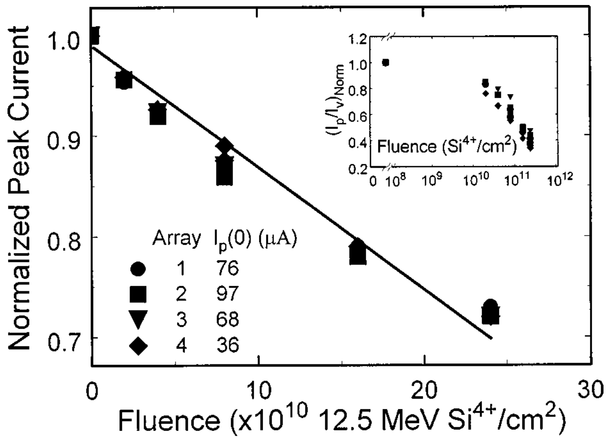

FIG. 2. Normalized peak current $I_p(\Phi)/I_p(0)$ vs fluence for four arrays. Values of $I_p(0)$ are given in the legend. $I_p(\Phi)$ decreases linearly with fluence for each array. Solid line: best fit to data. Inset: normalized peak-to-valley current ratio vs ion fluence.

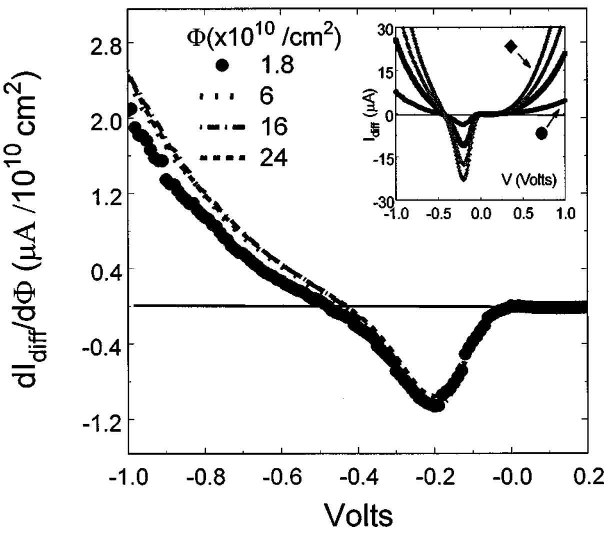

FIG. 3. Inset: The difference current $I_{\text{diff}}=I(\Phi)-I(0)$ vs voltage for various fluences. Main body: $dI_{\text{diff}}/d\Phi$ vs voltage for irradiated array. Two independent effects of radiation damage are identified: an increase in leakage current and a decrease in resonance current. ◆ in inset represents highest fluence.

In order to examine radiation damage in the RTDs in more detail, it is useful to subtract the $I-V$ curve of an irradiated array from that of the unirradiated array. The result of this procedure is shown in the inset of Fig. 3, where $I_{\text{diff}}\equiv I(\Phi)-I(0)$ is plotted against voltage at various fluences. Two trends are obvious. First, for voltages near -0.2 V, MeV ion damage decreases the resonant tunneling current. Second, for voltages outside the resonance, the same damage increases the leakage (i.e., nonresonance) current.

The two trends are easier to see in the main body of Fig. 3, where the fluence-normalized differential current $dI_{\text{diff}}/d\Phi$ is plotted versus voltage for various fluences. As in the inset, the curve has two components. The part due to leakage can be fit by

$$(dI/d\Phi)_{\text{leak}}=2.2|V|^3. \tag{2}$$

The second important component in Fig. 3 is the fluence-independent decrease in the resonant tunneling peak. This component is fit by a Maxwell–Boltzmann distribution

$$\left(\frac{dI}{d\Phi}\right)_{\text{res}}=-AV^2e^{-25V^2}, \tag{3}$$

where $A=65\,\mu\text{A}/10^{10}\,\text{cm}^2$, and V is in volts. The sum of Eqs. (2) and (3) fits the data in Fig. 3 very well.

Integrating Eq. (3) with respect to Φ gives the tunneling current I_{res} as a function of fluence and voltage

$$I_{\text{res}}(\Phi,V)=I_{\text{res}}(0,V)-A\Phi V^2e^{-25V^2}. \tag{4}$$

Before discussing the implications of Eq. (4), we briefly compare I_{res} and I_p. I_p is an empirical parameter representing the *total* current $I_{\text{tot}}(\Phi,V)$ at the peak of the $I-V$ curve. It may include contributions from leakage, and occurs at different voltages (V_p) for different fluences. I_{res} excludes leakage effects; it describes the entire resonance, and the position of its peak is independent of fluence. In other words

$$I_{\text{tot}}(\Phi,V)=I_{\text{leak}}(\Phi,V)+I_{\text{res}}(\Phi,V) \tag{5}$$

and

$$I_p(\Phi)=I_{\text{tot}}(\Phi,V_p). \tag{6}$$

It can be seen from Eq. (4) and Fig. 3 that although the amplitude of the resonance current decreases linearly with fluence, its shape remains fixed. Therefore, the parameters that determine the resonance shape must be unaffected by irradiation. These parameters are the heights and widths of the barriers in an RTD, the Fermi energy, the resonant energy of the quantum well, and the carrier effective mass.[5] This means that radiation-induced changes in the preceding parameters are not responsible for the observed decreases in the peak current.

The next most obvious factor to possibly affect I_p is the leakage current. However, the leakage current *increases* with increasing fluence, and so cannot contribute to the decrease in I_p.

In conclusion, we find that the linear decrease of I_p and I_{res} with Φ is caused neither by changes in leakage current nor by changes in the device parameters mentioned above. One possible explanation is that scattering of electrons from radiation-induced defects impedes tunneling by removing carriers from the narrow, dimensionally-constrained region of k space in which tunneling is allowed.

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