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Radiation tolerance of Si/Si$_{0.6}$Ge$_{0.4}$ resonant interband tunneling diodes

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The effect of 2 MeV proton irradiation on the current–voltage (IV) characteristics of Si/Si$_{0.6}$Ge$_{0.4}$ resonant interband tunneling diodes (RITDs) is reported. A fluence of 5×10^{14} H$^+$/cm^2 causes the peak current to increase by about 4% the valley current to nearly double and the peak-to-valley current ratio to be reduced by about half. At comparable fluences, most minority carrier diodes are inoperational. Radiation-induced changes are compared to changes in the IV curves of irradiated Si- and Ge Esaki diodes, GaSb-based RITDs and InP-based resonant tunneling diodes. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1710719]

I. INTRODUCTION

Resonant tunneling diodes and resonant interband tunneling diodes (RTDs and RITDs) offer several advantages over conventional electronic devices in terms of high speed and low power.[1] Si/Si$_{0.6}$Ge$_{0.4}$ (SiGe) RITDs are of particular interest due to their potential for integration into conventional silicon-based circuitry.[2–7] However, in order to be useful in satellite applications SiGe RITDs must be able to withstand the harsh radiation environment of Earth's geomagnetic belts.

Perhaps the best way to create controlled amounts of disorder is to use particle irradiation. In addition to being useful in determining space survivability, radiation-damage experiments can be used to develop postfabrication techniques to improve device performance and, through perturbation, to provide insight into the physics of device operation.[8] In the present study, 2 MeV protons were used to create defects (mainly vacancies and interstitials) in SiGe RITDs. Disorder-induced changes in the current–voltage (IV) characteristics of the devices were determined, then compared to particle-induced changes in other diode types such as AlAs/InGaAs/InAs/InGaAs/AlAs RTDs grown on InP, InAs/AlSb/GaSb RITDs grown on GaAs, Si Esaki diodes and Ge Esaki diodes.[9–15]

II. EXPERIMENT

SiGe RITDs were grown on a p^+ Si substrate by using molecular beam epitaxy and patterned using standard photolithography techniques into devices having diameters between 10 and 75 μm. The key features of the RITDs are an 80 nm p^+ substrate contact layer, a p^+ δ-doped layer, a 6 nm undoped spacer layer composed of 4 nm Si$_{0.6}$Ge$_{0.4}$ and 2 nm Si; a n^+ δ-doped layer and a 100 nm n^+ surface contact layer. Details on the structure and growth are presented elsewhere.[2]

In a typical experiment, IV curves were obtained for as many as 100 devices by measuring the current passing through the RITDs as the applied voltage was swept from -1.5 to 1.5 V. Devices were then irradiated with 2 MeV protons to a given fluence, Φ, and the IV curves were remeasured. This process was repeated up to a maximum fluence of $\Phi=1\times10^{15}$ H$^+$/cm^2. In all cases incident particles traversed the devices without significant loss of energy, and hence created uniform damage profiles.

Five parameters were determined from each IV curve—the peak and valley currents, I_p and I_v, the peak and valley voltages, V_p and V_v, and the peak-to-valley current ratio, PVCR$\equiv I_p/I_v$. For the 75-μm-diam devices the average preirradiation values and standard deviations of I_p, I_v and PVCR were 36.3±0.3 mA, 11.7±1.3 mA and 3.10±0.12, respectively. For smaller devices, I_p and I_v scale with area without affecting the PVCR.

III. RESULTS AND DISCUSSION

Typical IV curves are shown in the inset of Fig. 1 for an unirradiated and an irradiated device. A fluence of 1×10^{15} H$^+$/cm^2 reduced the PVCR from 3.6 to about 1.2. The roughly N-shaped IV characteristics, now familiar for SiGe RITDs, are seen at all fluences. The general effect of proton irradiation is to increase the nontunneling (leakage) current while causing a slight increase in the peak current. Similar effects are observed on e^-- and n^0-irradiated Esaki diodes[12–15] and H$^+$-irradiated GaSb-based RITDs.[11] Since leakage currents are sometimes regarded as a type of tunneling current, we specify that "leakage" refers here to current arising from defect-assisted transport of carriers across a device.

The effect of radiation damage on the PVCR is shown in the main body of Fig. 1. Below about $\Phi=10^{12}–10^{13}$ H$^+$/cm^2, no radiation-induced changes are ob-

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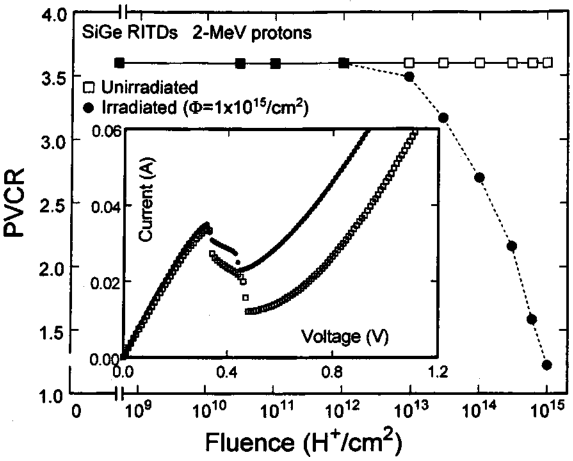

FIG. 1. Peak-to-valley current ratio vs 2 MeV proton fluence for irradiated SiGe RITDs. Inset: current–voltage curves for an unirradiated and an irradiated device. Minority carrier devices begin to degrade around 10^{10}–10^{11} 2 MeV H^+/cm^2 and are generally seriously degraded by 10^{13} H^+/cm^2.

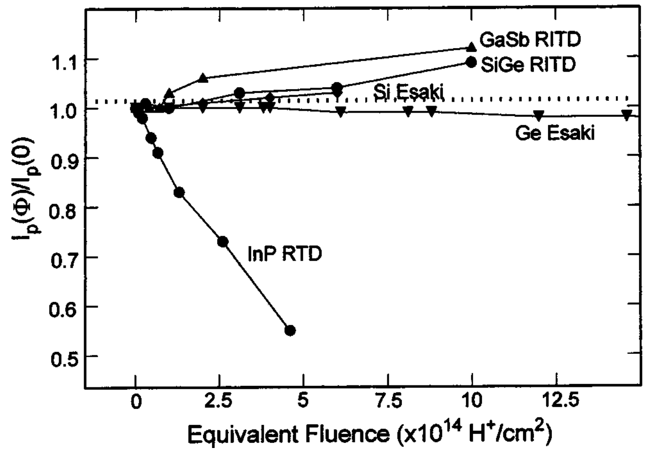

FIG. 3. Normalized peak currents vs equivalent fluence for Ge-and Si Esaki diodes (see Refs. 12, 14) SiGe RITDs, InP-based RTDs (see Refs. 8–10) and GaSb RITDs (see Ref. 11). Error bars on the SiGe data are approximately the same size as the symbols. Dashed horizontal line serves to guide the eye.

served. The same result was obtained for all measured devices regardless of diameter. (Device diameter had no effect on the radiation sensitivity of any parameter considered here.) In comparison, silicon-based solar cells and other minority carrier diodes begin to degrade at 2 MeV proton fluences between about 10^{10} and 10^{11} H^+/cm^2, and are generally seriously degraded by $\Phi = 10^{13}$ H^+/cm^2. Only majority carrier diodes such as InP-based RTDs display a degree of radiation tolerance comparable to that of the SiGe RITDs of Fig. 1.[9]

Values of $I_v(\Phi)/I_v(0)$ for a typical SiGe RITD are shown in Fig. 2 plotted versus fluence. Also shown are values of $I_v(\Phi)/I_v(0)$ for InP-based RTDs, GaSb-based RITDs and Si- and Ge Esaki diodes. Normalizing $I_v(\Phi)$ by $I_v(0)$ removes differences due to device size and material properties, and emphasizes the effect of irradiation on I_v. Because the Esaki diodes were irradiated with fast fission neutrons and the RTDs with 3 MeV helium ions, a standard technique based on the energy lost to displacement damage was used to convert n^0 and He^+ fluences to equivalent fluences of 2 MeV protons.[9] An average 3 MeV helium ion, for example, displaces about 10.3 times more atoms than a 2 MeV proton, which displaces about 15.5 times more atoms than an average fast fission neutron.

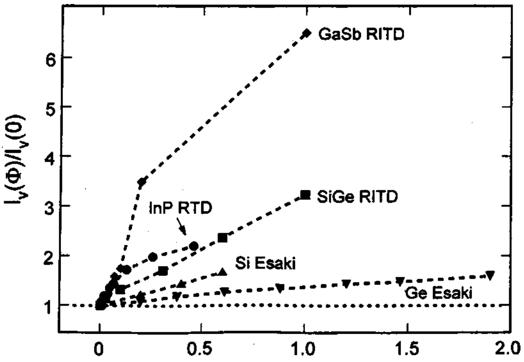

FIG. 2. Normalized valley current vs equivalent fluence for Ge-and Si Esaki diodes (see Refs. 12, 14) SiGe RITDs, InP-based RTDs (see Refs. 8–10) and GaSb RITDs (see Ref. 11). Error bars on the SiGe data are approximately the same size as the symbols.

As can be seen in Fig. 2, the valley current increases with increasing fluence for all devices. Comparable behavior is observed for many other kinds of diodes. In conventional *p-n* diodes, for instance, irradiation increases the reverse-bias leakage current in proportion to the induced defect concentration and the fluence.[16] In solar cells, it increases the dark current.[17] In the valley region of an Esaki diode's *IV* curve, leakage current, also referred to as excess current, has been attributed to conduction via localized defect gap states.[18]

The most disorder-tolerant devices, as shown in Fig. 2, are the Esaki diodes. Then in decreasing order are SiGe RITDs, InP-based RTDs and GaSb RITDs. This result is interesting because if SiGe RITDs were true Esaki diodes, their I_v-vs-Φ curves might be expected to fall between the Si and Ge Esaki data in Fig. 2. One possible explanation is that a structural factor such as the strained layer epitaxy in the SiGe RITDs causes an enhanced sensitivity to disorder. This possibility could be explored if radiation damage experiments were performed on similar devices grown without strained layers.

Values of $I_p(\Phi)/I_p(0)$ for the various diodes are shown plotted versus equivalent fluence in Fig. 3. Again, the Esaki diodes are the least affected by radiation damage, followed, respectively, by SiGe RITDs, GaSb RITDs, and InP-based RTDs. The peak current in the RTDs decreases rapidly with increasing defect concentration, while in the other devices it changes more slowly. The rapid decrease of the peak current in InP-based RTDs is due to strict dimensional constraints on the resonant tunneling state, wherein radiation-induced defects in the quantum wells scatter carriers out of resonance with high efficiency. In contrast, radiation-induced changes in the peak current of Esaki diodes have been attributed to leakage current increases and other effects. The mechanism for the radiation-induced changes in the peak current of the SiGe RITDs reported on here is not yet clear.

IV. CONCLUSION

In conclusion, 2 MeV proton irradiation experiments on SiGe RITDs show that these devices possess a high degree of radiation tolerance. As a result they are potentially very useful in space radiation environments.

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