DOPING DENSITY STRIATION EFFECTS IN STUDIES OF THE METAL–NONMETAL TRANSITION IN HEAVILY DOPED SEMICONDUCTORS ☆

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Significant oscillatory doping density inhomogeneities – striations – are reportedly a commonplace phenomenon in germanium and silicon crystals. Schottky barrier tunneling data on heavily doped and irradiation compensated silicon are presented which are consistent with the presence of such striations. The need for considering striations in studies of the metal–nonmetal transition is emphasized.

Introduction. It is well known to crystal growers that small scale oscillatory doping inhomogeneities – striations – are a commonplace occurrence in germanium and silicon crystals. Evidence of striations was first observed in single crystal silicon by Pfann and Scaff in 1949 [1]. Doping density variations of this nature occur in Czochralski grown crystals reportedly due to the asymmetry of the temperature distribution in the melt. The surfaces of constant impurity concentration in Czochralski crystals are helical, separated by the distance the crystal grows vertically in one rotation [2]. In float-zone crystals these variations are a result of the supercooling required to initiate growth from the melt [3]. Variations in the resistivity of as much as 40 to 50% have been reported in crystals grown by the float zone method [3,4].

It is important to note that striations are present in all silicon and germanium crystals grown in the manners described above and that the severity of the striations increases as the impurity levels nears saturation. Attempts to improve the crystal growth process to reduce the doping density variations have met with limited success [5]. Another important feature of these variations is that they do not usually lie in the growth plane, since the solid–liquid interface tends to be hemispherical in shape. This implies that even a crystal cleaved in the growth plane will be intersected by many oscillations in the doping density.

Despite this knowledge of striations, little work on their effects has been published. Most information is limited to the effects on devices such as unusually low breakdown voltages in high power silicon [6] diodes and dark current characteristics of diode array tubes [7]. Neutron transmutation doping is being used commercially in an effort to alleviate such problems [8].

The existence of striations and their potential effects have been neglected in discussions of the metal–nonmetal transition. We want to call this problem to the attention of researchers in this field and discuss their manifestation in our studies of the tunneling in Schottky barriers on compensated degenerate silicon.

Experimental procedure. The samples used were cut from Si : P and Si : As float-zone crystals heavily doped to the 2×10^{19} cm^{-3} range and grown in the (111) directions. Average doping density determinations were made by taking resistivity measurements of nearby samples in the boule and comparing to the Irvin curve [9]. In the case of Si : As samples, neutron activation analysis was also performed.

Ohmic contacts to the silicon were made by gold bonding techniques. The samples were cleaved under

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high vacuum exposing a (111) growth plane to an evaporating stream of indium in a system based on the methods used by Wolf and Compton [10]. Contacts to the indium were made using the photoresist techniques of Cullen et al. [11]. Based on measurements of the striation widths of these samples, each junction should have covered an area which included at least one striation oscillation.

The incremental resistance ($\mathrm{d}V/\mathrm{d}I$) was measured at liquid helium temperatures using standard techniques [12]. A magnetic field of 1 kG was applied to quench superconductivity in the indium. The samples were irradiated with a 6.25 MeV proton beam in the University of Kentucky van de Graaff facility. A final collimator with a 0.375 mm diameter hole, about twice the diameter indium dot, was aligned in front of the selected junction. This allowed a small fraction of the total beam cross section (approximately 2 cm in diameter) to impinge on the junction region. The temperature of the sample rose only a few degrees above room temperature during irradiation.

Results and discussion. Detailed comparisons of experiment and theory have been reported for tunneling in heavily doped and uncompensated germanium [13]. Work has also been done on uncompensated silicon [14,15]. The data have been explained in terms of tunneling between extended states in the conduction band of the semiconductor and extended states in the metal. For low temperatures a temperature independent smooth curve with a resistance peak in forward bias is predicted and observed. The peak is displaced from zero bias by a voltage equal to μ_F/e, where μ_F is the Fermi level referred to the bottom of the semiconductor conduction band.

Results for heavily doped and strongly compensated silicon and germanium have also been described in the literature [16,17]. The characteristic curves have a large resistance peak at zero bias and show strong temperature dependence, the peak getting sharper and the rate of change of the zero bias resistance with temperature increasing, as T is decreased. The conductance at zero bias has been found to decrease with temperature as $\mathrm{e}^{-c/T^{1/4}}$ in 1 K to 4 K temperature range. These results have been explained in terms of variable range phonon assisted tunneling [16,17] to localized states in the semiconductor. For heavily doped and strongly compensated material tunneling occurs to localized states because the semiconductor Fermi level has been lowered into such states in the tail of the impurity band by the strong compensation.

Data for a silicon sample with intermediate compensation are shown in fig. 1. A relatively small temperature dependent resistance peak near zero bias *and* a temperature independent peak in forward bias are evident. The sample was subjected to several previous irradiations and as a result, the effects of various levels of compensation were observed in the same sample. The forward bias peak showed a gradual decrease in bias voltage with each successive irradiation from an initial value of 29 mV, in agreement with the Fermi level relative to the bottom of the conduction band in the unirradiated material, to a value of approximately 20 mV for the irradiation level shown in fig. 1. Compensation causes a decrease in the Fermi level; hence for tunneling to extended states in the semiconductor this decrease in peak position with irradiation is expected. It is reasonable, therefore, to associate tunneling via extended states with this temperature independent forward bias peak which shows gradual traceable changes with irradiation. The simultaneous occurrence of this peak and the near zero bias peak in the same sample, seemingly contradictory, is consistent with tunneling to silicon in which the doping density varies across the face of the junction. Considering for simplicity a model in which highly doped and lowly doped material dominate, one has a parallel combination with these dopings. For part of the junction the doping is high, the compensation low and tunneling proceeds via extended states in the semiconductor. For the remaining area of the junction, where the doping is low, the same level of irradiation leads to higher levels of compensation and tunneling proceeds via localized states. The resistivity is, of course, expected to be higher for the latter, however the resistance of each junction type is determined by the area involved as well as the resistivity and the total resistance is that of the parallel combination.

Note that the rate of change of the peak with temperature decreases as the temperature is lowered. This saturation is expected for the parallel combination. Other features of the data are qualitatively consistent with the parallel tunnel junction model. The peak is slightly offset from zero bias indicating a true zero bias conductance dip added to a gradually decreasing conductance background. The peak moves closer to zero bias at lower temperatures consistent with a sharpen-

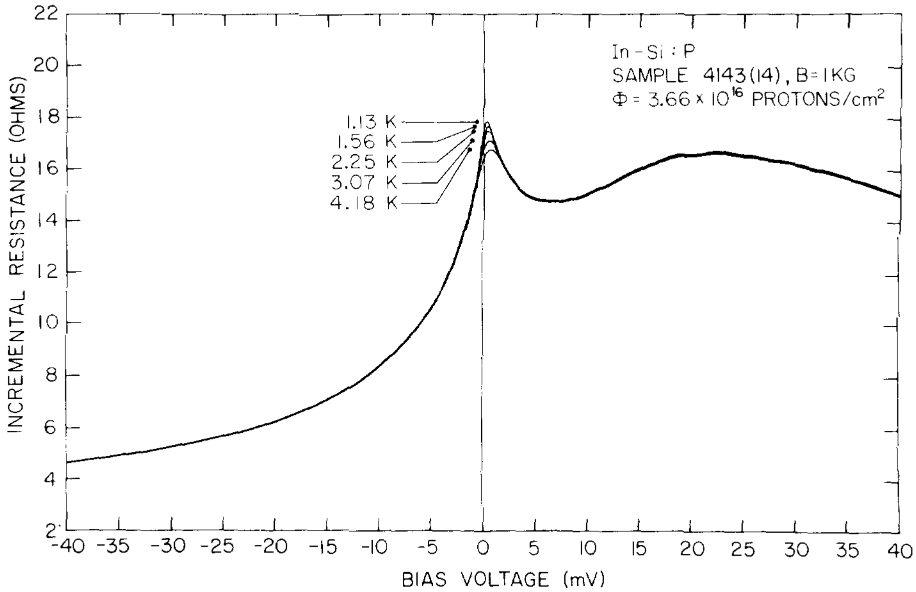

Fig. 1. Incremental resistance as a function of bias voltage at temperatures in the 1 K to 4 K range for an irradiated In–Si:P sample with initial doping of 2.6×10^{19} cm^{-3}.

ing of the conductance dip. With increased irradiation not only does the peak become more prominent but again it moves closer to zero bias. Increased irradiation causes more of the junction to be highly compensated, decreasing relatively the effect of the direct tunneling portion of the junction.

From this discussion one would expect the zero bias conductance to fit to $G = G_0 + G_1 \mathrm{e}^{-c/T^{1/4}}$, where G_0 is the temperature independent direct tunneling conductance and the other term is the variable range phonon assisted tunneling contribution. A fit to this equation for the data presented in fig. 1 is shown in fig. 2. Similar good agreement has been observed for all values of irradiation for which a temperature dependent peak was discernible. For the highest value of irradiation essentially a straight line was observed in agreement with all of the junction, including the highest doped regions, being strongly compensated. For this case, as expected, no forward bias peak was observed. These results are different from those of Wolf et al. [17] for $N_D = 4.5 \times 10^{18}$ cm^{-3}, chemically compensated, Czochralski crystal junctions for which the zero bias conductance peak showed pure $\mathrm{e}^{-c/T^{1/4}}$ behavior in samples which also had a forward bias peak. Their peak appeared in far forward bias (approximately 40

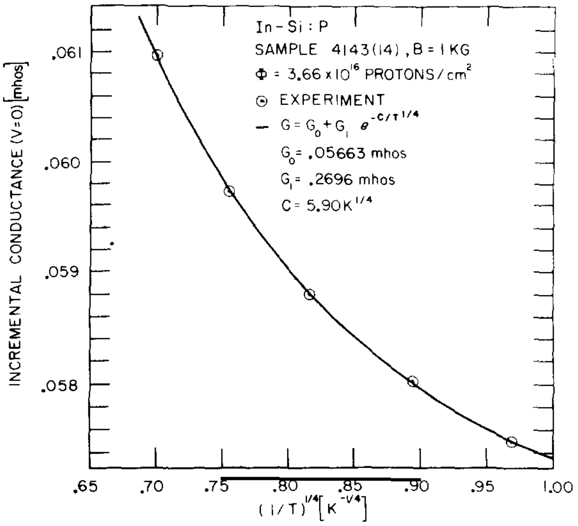

Fig. 2. A fit of the zero bias conductance data of fig. 1, shown on a ln G versus $1/T^{1/4}$ plot.

mV) and they suggested it could be associated with the end of a broad band of impurity states below the conduction band. Another noteworthy feature of our irradiation data is that over the entire range studied the ratio $G_1 \mathrm{e}^{-c/T^{1/4}}/G_0$ increased with increasing irradiation as more of the junction became strongly compensated.

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