Carrier Dynamics and Space-Charge Dipoles in High-Purity Silicon

G. L. Fong [a] and N. M. Haegel
Department of Materials Science and Engineering, University of California, Los Angeles, California 90024

J. T. Walton
Engineering Science Department, Lawrence Berkeley Laboratory, Berkeley, California 94720
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Direct evidence of space-charge dipole formation resulting from minority-carrier injection in a high-purity relaxation semiconductor has been observed for the first time. Small signal ac measurements are utilized to monitor the capacitance of a high-purity silicon structure as the temperature is decreased from 70 to 11 K. An increase in capacitance at 22 K is attributed to the formation of a charge dipole as a consequence of majority-carrier depletion in the relaxation regime.

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Carrier dynamics in very high resistivity semiconductors are fundamentally different than those which characterize the lifetime regime. The classification of semiconductor transport behavior into relaxation and lifetime regimes was first suggested by van Roosbroeck over thirty years ago [1]. The lifetime regime is defined as the regime where the excess-carrier recombinative lifetime is greater than that of the dielectric relaxation time ($\tau_d < \tau_0$). The relaxation regime implies the converse situation ($\tau_d > \tau_0$). Most theoretical and experimental semiconductor studies have been done in lifetime regime materials. In contrast, relaxation semiconductors have received relatively little attention. Many fundamental questions remain concerning nonequilibrium transport in large-band-gap semiconductors, amorphous and trap-dominated semiconductors, and high-purity semiconductors at low temperatures. Fundamentally different and novel transport behavior can be observed in these high resistivity solids which are capable of supporting extensive space-charge domains.

Theoretical studies have predicted that minority-carrier injection into a relaxation semiconductor would result in majority-carrier depletion and the formation of space-charge regions [2]. Models solving the full set of coupled transport equations with Poisson's equation also indicate that relaxation semiconductors can support space-charge domains and regions of high recombination [3,4].

Essential predictions of relaxation theory include the formation of a space-charge dipole near an injecting contact and the existence of a recombination front where the excess carrier concentration (np) product goes through a maximum. The dipole is created by the combination of majority-carrier depletion near the injecting contact and a corresponding excess of majority carriers further from injection which is required to maintain current continuity. Although the concept of a space-charge dipole has been a cornerstone of the relaxation theory, there has been no experimental proof of the phenomenon. Previous experimental studies in relaxation semiconductors were limited by high defect densities which obscured much of the unique physical phenomena when the dielectric relaxation time begins to exceed the excess-carrier recombinative lifetime. In this work, capacitance measurements of a high-purity silicon diode provide direct evidence of a space-charge dipole in the relaxation regime.

Measurements were done on a n^+-p-p^+ radiation detector designed and fabricated at Lawrence Berkeley Laboratory [5]. The device schematic in Fig. 1 illustrates the physical and doping profile. The bulk material was float-zone high-purity Si with a resistivity of 4000–6000 Ω cm at 300 K. The shallow acceptor (boron) concentration was approximately 2×10^{12} cm^{-3}. The p^+ region was formed by a 25-keV boron implant; the n^+ region by phosphorus diffusion. The diode was passivated by oxidation. The injecting contact area was 0.5 mm^2; the bulk region length was approximately 380 μm. A compensating p layer of approximately 3 μm was implanted prior to oxidation in order to prevent inversion at the SiO_2/Si interface. Gold and aluminum metallization was applied to p^+ and n^+ regions, respectively.

Frequency response characterization was performed in a variable temperature cryostat. The diode was soldered to a cold finger which was attached to the cooling plate of the cryostat. Using a summing amplifier, an ac voltage was superimposed upon the dc bias to the silicon device.

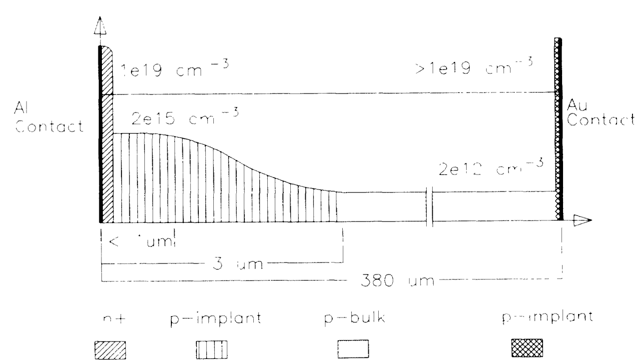

FIG. 1. Doping profile and geometry of Si diode.

Current through the diode was monitored with a transconductance amplifier; magnitude and phase data were measured using a lock-in amplifier.

This experiment investigated transport in a low-trap-density semiconductor where majority-carrier depletion under minority-carrier injection dominates. The frequency response of a high-purity silicon diode was measured under minority-carrier injection at various temperatures. Experiments were done in the material's lifetime regime ($\approx$ 70–30 K) and in the relaxation regime ($\approx$ 25–14 K) to study changes in transport behavior as the transition occurs. Decreasing temperature transforms the p-type silicon bulk from a lifetime to a relaxation semiconductor by shallow acceptor freeze-out since the dielectric relaxation time ($\tau_d = \rho\epsilon_0\epsilon_r$) varies as the resistivity ($\rho^{-1} = q\mu_p p$). The experiment provided magnitude and phase data which were used to calculate real and imaginary components (σ_r, σ_i) of the conductance. Capacitance at a given frequency was determined by the following formula: $C = \sigma_i/\omega$. Conductance was defined simply as $G = \sigma_r$.

Figure 2 presents the ac capacitance as a function of frequency for three different temperatures. There is clear evidence of an additional capacitive mechanism as the temperature is lowered from 55 to 22 K. We attribute this increase in capacitance to the formation of a charge dipole in relaxation regime conduction. Depletion of majority carriers under minority-carrier injection is responsible for the net negative charge region in the bulk p region. The negative charge is composed of excess injected electrons and ionized acceptor cores. However, current continuity must be maintained even as minority-carrier concentration decreases further into the bulk. Thus, a region of excess majority carriers must exist near the p^+ contact. A space-charge dipole is formed internally, although macroscopically the device is space-charge neutral.

Dipole capacitance is defined as the product of the amount of space charge and the distance between the center of mass of the space-charge regions ($C_{\text{dipole}} \propto Qd$). Thus, the capacitance varies with the carrier profiles which are determined by temperature and injection level. As temperature is reduced past the transition temperature, the number of free holes decreases exponentially. Therefore, dipole capacitance diminishes as the number of holes available for depletion drops. Increasing injection into the diode at a given temperature augments the depletion in the near contact region which increases dipole capacitance. A sum of two exponentials characterizes the frequency response. The dipole frequency response is responsible for the low-frequency behavior while carrier lifetime determines the higher-frequency rolloff [6]. In relaxation semiconductors, higher injection increases the carrier lifetime which decreases high-frequency rolloff of the response. Structural distinctions in frequency response begin to disappear as the times become similar.

Conductance and capacitance versus temperature exhibit similar behavior (Fig. 3). In the lifetime regime, conductance decreases with decreasing temperature. However, as the dielectric relaxation time exceeds the recombinative lifetime, majority-carrier depletion begins to cause a conductivity enhancement as electron and hole diffusive current components become additive. Correspondingly, the capacitive effects of a space-charge dipole begin to dominate the low-frequency behavior as injected minority carriers are unscreened and majority-carrier depletion occurs. After the relaxation behavior dominates, further decreases in temperature reduce both conductance and capacitance. This is attributed to a decrease in number of ionized majority carriers available for depletion and the associated diminishing concentration gradients. The capacitive decrease is approximately exponential since the ionized acceptor concentration falls

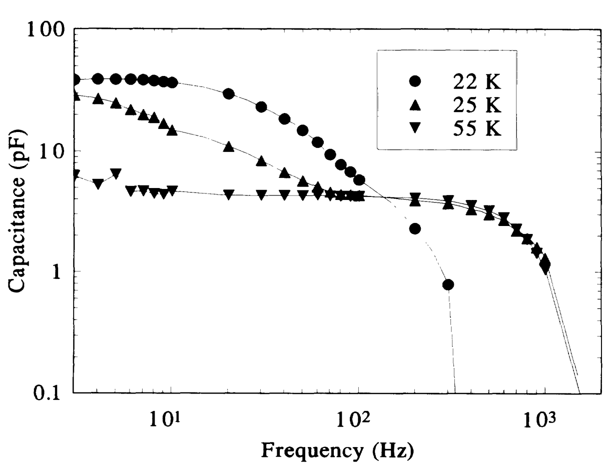

FIG. 2. Capacitive frequency response of high-purity silicon at 22, 25, and 55 K.

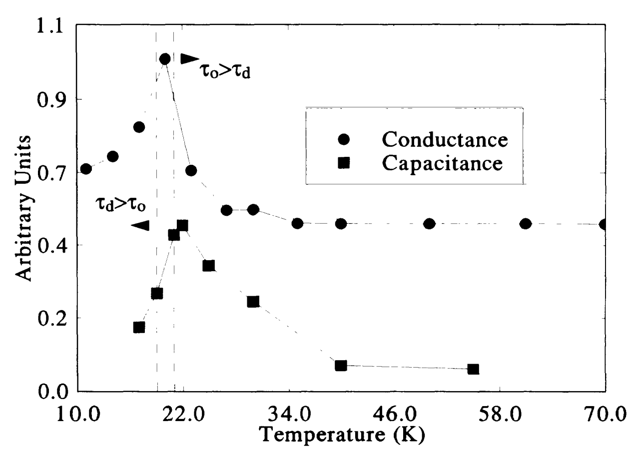

FIG. 3. Low-frequency (5 Hz) conductance and capacitance vs temperature. Lifetime and relaxation regimes indicated by ($\tau_0 > \tau_d$) and ($\tau_d > \tau_0$), respectively.

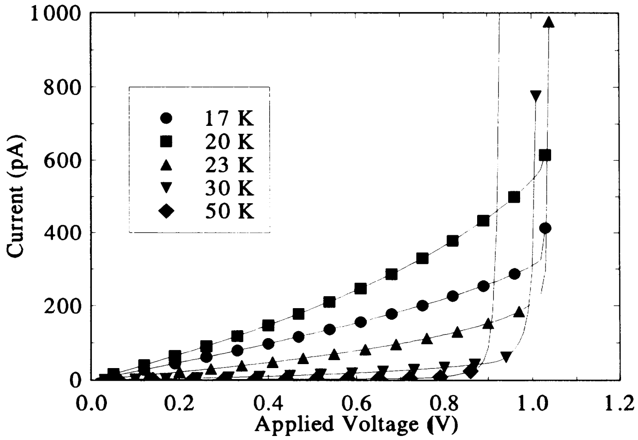

FIG. 4. I-V characteristics of high-purity silicon at 17, 20, 23, 30, and 50 K. Curves were calculated by integrating 5-Hz ac conductance data (dI/dV) across the dc bias range.

exponentially with temperature. Mobility increases with decreasing temperature since phonon scattering diminishes as $T^{-3/2}$. The conductance behavior in the relaxation regime therefore depends upon a product of an exponential and a power.

Figure 4 presents the I-V characteristics of the diode at various temperatures. The curves were obtained by integrating low-frequency ac conductances ($G=dI/dV$) over the biasing voltage. This result confirms previous experimental work by Cavicchi and Haegel [7] which established the predicted increase in conductance as carrier transport properties become dominated by the dielectric relaxation time rather than the carrier lifetime. The curves from 70 to 30 K indicate a constant conductance (within the sensitivity of the measurement system) at a given voltage. The conductance increases as temperature is decreased in the relaxation regime. At 20 K the conductance is a maximum. Further decreases in temperature lower the conductivity as carrier freeze-out dominates over the additive diffusive transport.

Majority-carrier depletion and dipole formation can be observed in this high resistivity silicon because of the relatively low trap density. In trap-dominated semiconductors, such as semi-insulating GaAs, majority-carrier depletion is suppressed and majority-carrier enhancement may occur near the injecting contact when injected minority carriers become localized in deep traps [8–10]. Trapped minority carriers provide a Coulombic attraction of majority carriers toward the region. For this reason, the space-charge dipole and majority-carrier depletion have never been observed in earlier experimental work concentrating on trap-dominated semi-insulating materials [11,12].

In conclusion, this work presents the first direct experimental evidence of charge dipole formation under injection in high-purity silicon at cryogenic temperatures. Capacitance and conductance temperature profiles are consistent with models of majority-carrier depletion as a result of minority-carrier injection in the relaxation regime.

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[a]Currently on leave from Hughes Aircraft Company.

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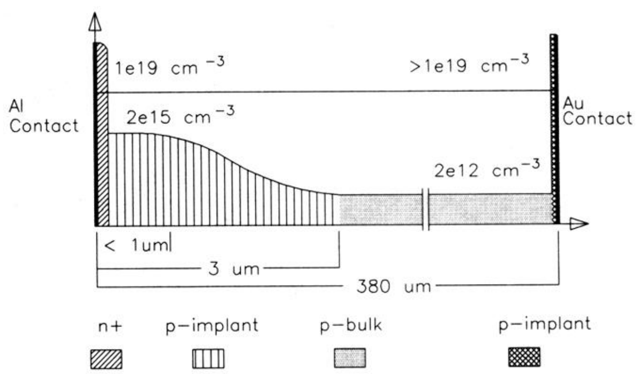

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