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Insulator-to-Metal Transition in Sulfur-Doped Silicon

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We observe an insulator-to-metal transition in crystalline silicon doped with sulfur to nonequilibrium concentrations using ion implantation followed by pulsed-laser melting and rapid resolidification. This insulator-to-metal transition is due to a dopant known to produce only deep levels at equilibrium concentrations. Temperature-dependent conductivity and Hall effect measurements for temperatures $T > 1.7$ K both indicate that a transition from insulating to metallic conduction occurs at a sulfur concentration between 1.8 and $4.3 \times 10^{20}$ cm$^{-3}$. Conduction in insulating samples is consistent with variable-range hopping with a Coulomb gap. The capacity for deep states to effect metallic conduction by delocalization is the only known route to bulk intermediate band photovoltaics in silicon.

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Recently, it has been suggested that high efficiency photovoltaic (PV) devices could be fabricated by including an intermediate band of electronic states within the band gap of a traditional PV material [1]. This intermediate band could facilitate absorption of low energy photons and increase photocurrent without reducing cell voltage. An intermediate band photovoltaic (IBPV) device could thus exceed the Shockley-Queisser efficiency limit for single-gap materials [2]. Evidence of this effect has been observed in dilute compound-semiconductor alloys [3] and quantum dot structures [4]. Another proposed IBPV design is a semiconductor doped with impurities that introduce electronic states deep in the band gap [5]. Deep-level impurities have long been considered candidates for absorbing low energy photons [6]; however, they are generally active in nonradiative processes that reduce carrier lifetime and thus reduce PV device efficiency. It has been proposed that these parasitic effects could be avoided if the electrons associated with deep-level impurities delocalize, for example, via a Mott metal-insulator transition [5]. In this scenario, the strong electron-phonon coupling associated with localized states—ultimately responsible for facilitating nonradiative processes—would vanish. Optical transitions facilitated by deep levels could then be exploited while avoiding their parasitic effect on carrier lifetime; evidence of this lifetime-recovery effect has been reported for Si doped with high titanium concentrations [7]. However, direct evidence of a delocalization transition in Si doped with deep-level impurities—measured as an insulator-to-metal (I–M) transition—has not previously been observed.

In this Letter we report that an I–M transition occurs in sulfur-doped crystalline silicon. When doping is performed as described below, the transition occurs at sulfur concentrations between 1.8 and $4.3 \times 10^{20}$ cm$^{-3}$. We observe the transition by measuring the temperature-dependent conductivity and Hall effect between 1.7 K and 293 K. For samples doped to a peak sulfur concentration $c_{pk} = (3.6 \pm 0.7) \times 10^{20}$ cm$^{-3}$, the carrier concentration does not change over the temperature range studied, a negative temperature coefficient in the conductivity is observed below 4 K, and conductivity over 100 ($\Omega \cdot$ cm)$^{-1}$ persists to $T < 1.7$ K. At the lowest sulfur concentration studied [$c_{pk} = (1.2 \pm 0.3) \times 10^{20}$ cm$^{-3}$], sample conductivity exhibits strong thermal activation, with donor freeze-out and variable-range hopping observed at low temperatures. The remaining samples exhibit some of both sets of behaviors. Conductivity at 2 K varies by a factor $10^6$ among samples in this relatively narrow sulfur concentration range.

In all samples, sulfur concentration exceeds the maximum solid solubility of sulfur in Si ($3 \times 10^{16}$ cm$^{-3}$) by a factor of about $10^4$ [8]. We achieve these concentrations using sulfur-ion implantation followed by nanosecond pulsed-laser melting and rapid resolidification [9]. This method has been demonstrated previously for doping with heavy chalcogens (S, Se, Te) [10,11]; similar doping concentrations have been achieved via fs-laser techniques [12]. For both techniques, Si doped with about 1% atomic sulfur exhibits strong sub-band gap absorption [10–12], an attractive optical property for IBPV devices.

The optical and electronic properties of Si doped with equilibrium sulfur concentrations have been reviewed [13] previously. Those experiments found that sulfur introduces deep-level electronic states 100–300 meV below the conduction-band edge, and that Si is an insulator under these conditions. Because these energy levels are far from the Si band edges, S:Si is a promising candidate for demonstrating IBPV devices. Density-functional calculations have explored nonequilibrium sulfur concentrations in Si [14], but no experimental studies of electronic transport have been reported yet.

Mott originally described the delocalization of donor electrons in a semiconductor host as an electron-screening effect [15]. At low donor concentrations, the electric field
exerted by a donor nucleus on its unpaired electron experiences only dielectric screening. In this regime, all ground-state electrons are localized. When the donor concentration increases above a critical donor concentration \( n_{\text{crit}} \), metallic screening produced by delocalized electrons eliminates the bound state and donor electrons delocalize. This transition is experimentally observed as an I–M transition. For a variety of systems [16], \( n_{\text{crit}} \) approximately satisfies

\[
a_{b}\, n_{\text{crit}}^{1/3} = 0.25,
\]

where \( a_{b} \) is the effective Bohr radius of donor electrons. For shallow levels in a doped semiconductor (such as P or B in Si), the I–M transition has been studied extensively [17]. In this case Bohr radii are on the order of 10 nm and Eq. (1) predicts \( n_{\text{crit}} \approx 10^{18} \text{ cm}^{-3} \), in good agreement with measured values [17]. Because the critical concentrations are less than the solubilities [18] of these elements in Si (\( > 10^{20} \text{ cm}^{-3} \)), traditional local-equilibrium growth techniques can readily provide high-quality metallic and insulating samples. Deep levels, alternatively, have more tightly bound electrons. Thus according to Eq. (1), the I–M transition should occur at higher concentrations (\( n_{\text{crit}} > 10^{18} \text{ cm}^{-3} \)) than for shallow donors. However, the maximum solubilities of deep-level impurities in Si are generally below \( 10^{15} \text{ cm}^{-3} \) [18]. Accordingly, equilibrium doping does not lead to an I–M transition for these elements in Si. By utilizing a nonequilibrium doping method, however, this work demonstrates an I–M transition in crystalline Si driven by a deep-level dopant.

Single-crystal Si wafers (boron doped, \( \rho = 25 \Omega \cdot \text{cm} \)) were commercially ion-implanted, nominally with 95 keV \( ^{32}\text{S}^{+} \) to doses of \((3, 7, 9, \text{ and } 10) \times 10^{15} \text{ cm}^{-2} \). The implanted region, amorphised by the implant, was melted using four spatially homogenized XeCl\(^*\) excimer laser pulses (fluence \( = 1.7 \text{ J} \cdot \text{cm}^{-2} \), \( \lambda = 308 \) nm, pulse duration 25 ns full-width at half-maximum) in laboratory ambient conditions. Using this process the melted region resolidifies as a single crystal free of extended defects, doped with about 1% atomic sulfur [10,11]. We quantified the sulfur concentration-depth profile using secondary ion mass spectrometry, identifying the peak concentration \( c_{pk} \) and the retained areal sulfur dose \( \Phi \). The sample preparation and characterization process have been described in detail previously [10,11]. We report on four samples here; we label them A, B, C, and D and outline their properties in Table I.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \Phi ) (10(^{15} ) cm(^{-2} ))</th>
<th>( c_{pk} ) (10(^{20} ) cm(^{-3} ))</th>
<th>( d_{\text{eff}} ) (nm)</th>
<th>( T_{0} ) (K)</th>
<th>( \sigma_{0} ) (( \Omega \cdot \text{cm} ))</th>
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<tr>
<td>A</td>
<td>9 ± 2</td>
<td>3.6 ± 0.7</td>
<td>250</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>B</td>
<td>10 ± 2</td>
<td>3.8 ± 0.8</td>
<td>260</td>
<td>⋯</td>
<td>⋯</td>
</tr>
<tr>
<td>C</td>
<td>4.3 ± 0.9</td>
<td>2.2 ± 0.4</td>
<td>250</td>
<td>9.05</td>
<td>3.20</td>
</tr>
<tr>
<td>D</td>
<td>3.0 ± 0.6</td>
<td>1.2 ± 0.2</td>
<td>260</td>
<td>326.5</td>
<td>2.46</td>
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Figure 1 shows the low temperature conductivity for all samples. At 2 K, conductivity differs by a factor 10\(^{3} \) among samples whose peak sulfur concentration varies by a factor of 3. Sample A exhibits a slightly negative temperature coefficient between 2 and 4 K (inset, Fig. 1). In Fig. 2, the carrier concentration at 2 K is plotted against the same value at room temperature. For samples with peak sulfur concentrations of at least \((3.6 ± 0.7) \times 10^{20} \text{ cm}^{-3} \), the low- and high-temperature carrier concentration are indistinguishable. For samples with lower sulfur concentrations, the carrier concentration at 2 K is significantly smaller than that at 293 K.

The metallic state is defined by finite conductivity as \( T \rightarrow 0 \), whereas insulators exhibit conductivity that must be thermally activated. As shown in Fig. 1, samples C and D exhibit strongly thermally activated conductivity and are clearly insulators. Samples A and B exhibit conductivities that vary only slightly over the measured temperature range, and appear to remain finite as \( T \rightarrow 0 \). Below 4 K, sample A exhibits a slightly negative temperature
behave as metals, while 10⋯ments of Si doped with shallow donors at just-metallic concentration; dashed line shows metallic behavior. Samples FIG. 2 (color online). Temperature dependence of carrier concentration. The conductivity of sample 1⋯experiments realized via nonequilibrium doping.

At low temperature, the conductivity of a doped semiconductor in the insulating state scales as

$$\sigma(T) = \sigma_0 \exp[-(T_0/T)^s].$$  \hspace{1cm} (2)

The value of the constant $s$ depends on the temperature and density of states at the Fermi level; the prefactor $\sigma_0$ and exponential activation $T_0$ are related to material parameters by different relationships for each value of $s$ [25]. We fit the conductivity of the insulating samples to Eq. (2) using several different exponents: $s = 1/4$, 1/2, and 1, corresponding to Mott’s variable-range hopping, variable-range hopping with a Coulomb gap, and nearest-neighbor hopping, respectively [25]. Both $s = 1/4$ and $s = 1/2$ provide reasonable fits, with average relative mean square errors of 1.7% and 1.0%, respectively, and fitting ranges restricted to $T < 20$ K and $T < 15$ K, respectively. Acceptable fits cannot be found using $s = 1$. The data and fits for $s = 1/2$ are shown in Fig. 3, with fitting parameters provided in Table I.

To determine the value of $s$, we replotted the data as $W = d \log(\sigma)/d \log(T)$ versus temperature on a log-log scale (inset, Fig. 3). For conductivity activated as in Eq. (2), the slope of $\log W$ versus $\log T$ yields the value of $-s$ [25]. By this analysis, sample $D$ yields $s = 0.43 \pm 0.06$—very close to $s = 1/2$—indicating that conduction likely occurs by variable-range hopping with a Coulomb gap in this sample [25]. The data for sample $C$ cannot be identified with a specific conduction mechanism; regardless, sample $C$ exhibits weaker temperature activation than sample $D$. In hopping conduction, this behavior is consistent with an increased electron correlation length [25], which would be expected as the dopant concentration approaches $n_{\text{crit}}$.

Finally, we comment on our calculation of $\sigma$. Both $c$ and $\sigma$ vary in the sulfur-doped region as a function of distance $z$ from the sample surface. The peak values can be related using $\sigma_{\text{pk}} = \alpha c_{\text{pk}}$, where $\alpha$ is a constant with dimensions.
The capacity for deep states to effect metallic conduction increases as Si for which the carrier lifetime is limited by shallow donors. A higher concentration of such states is required to overcome the limited lifetime. In conclusion, we observe an insulator-to-metal transition in Si doped with shallow donors by pulsed-laser melting. Conductivity and Hall effect data indicate that the transition occurs at a peak sulfur concentration of \(10^{-20}\) cm\(^{-3}\). Together with the definition of sheet conductivity, we can state that the peak conductivity represents a lower bound on the peak conductivity for reference.

In conclusion, we observe an insulator-to-metal transition in Si doped with sulfur via ion implantation followed by pulsed-laser melting. Conductivity and Hall effect data indicate that the transition occurs at a peak sulfur concentration between 1.8 and \(4.3 \times 10^{20} \) cm\(^{-3}\). At sulfur concentrations just below the transition, variable-range hopping with a Coulomb gap is observed along with a decrease in the conductivity at \(T = 1.7 \) K by a factor \(>10^6\) relative to metallic samples. The I–M transition reported in this Letter is driven by a deep-level impurity. The capacity for deep states to effect metallic conduction by delocalization is the only known route to bulk intermediate band devices, including photovoltaics, in materials such as Si for which the carrier lifetime is limited by nonradiative recombination.

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