Concentration-induced transition to a conductivity with a constant hopping length involving states near the Fermi level in a field effect in slightly compensated Si:B

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The low-temperature electrical conductivity of heavily doped Si:B films has been observed to increase and reach a plateau as the surface becomes depleted of majority carriers. The results are interpreted in terms of a concentration-induced transition to a new type of hopping conductivity.

If one changes the relative concentrations of the vacant and filled centers forming an impurity band by introducing excess charge carriers through the application of a field or injection from contacts, one can controllably shift the impurity levels with respect to the Fermi energy. One can thereby bring about a transition from a hopping conductivity described by an activation law at the maximum of the density of states to an essentially activationless conductivity involving states near the Fermi level. In doped bulk semiconductors, this type of hopping transport, with a characteristic decrease in activation energy with decreasing temperature, is described by a Mott law and is observed only at low temperatures.[1] In this letter we show that in the case of a field effect in the impurity band of slightly compensated silicon the conductivity involving states near the Fermi level exhibits a completely different behavior and may be manifested at much higher temperatures.

The experiments were carried out in the classical field-effect layout (Fig. 1a) on thin ($d = 0.5$ μm) p-Si:B films with a boron concentration $N_a = 1 \times 10^{18}$ cm^{-3}. Two p^+ contacts were applied to the films. The p-type layer was formed on an n-type Si:P substrate (the phosphorus concentration was $N_d = 1 \times 10^{15}$ cm^{-3}) by ion implantation of boron. The polysilicon field electrode, with dimensions of 100×100 μm, was insulated by a layer of a thermal oxide, SiO_2, with a thickness $d_{ox} = 620$ Å. The static conductivity σ of the p-type layer was measured as a function of the potential on the field electrode, V_g, by the method of Ref. 2 over the temperature range $T = 6$–300 K.

Figure 2 shows the field dependence $\sigma(V_g)$ for temperatures $T \geqslant 6$ K. The shape of the curves at $T \geqslant 20$ K corresponds to the classical picture of a monotonic decrease in σ due to a decrease in the surface concentration of majority carriers and an expansion of the depletion layer in the semiconductor with V_g (Ref. 3). At $T \leqslant 20$ K, the $\sigma(V_g)$ curves are fundamentally different. Near the transition from the regime of an enrichment of the Si surface with majority carriers to a regime of depletion, a minimum appears on the $\sigma(V_g)$ curves. The appearance of this minimum is accompanied

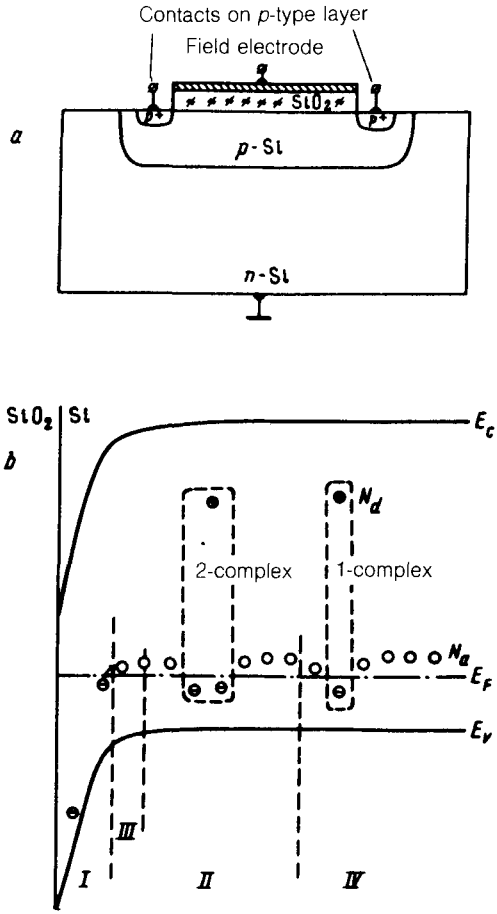

FIG. 1. The metal–oxide–semiconductor structure which was studied. a: Cross section. b: Band scheme of the space-charge region of Si for $V_g > V_g^*$. I—Region of the ionized boron impurity; II—region of 2-complexes; *3*—transition region; *4*—electrically neutral region.

by the formation of a clearly defined plateau on the plot of the conductivity. This behavior is a direct result of a sequential change in the transport mechanisms as a result of the field. It is manifested in a transition from a free motion of holes in the valence band (this is the enrichment regime) to a hopping electronic transport involving localized boron states (this the depletion regime). At sufficiently low temperatures, with flat bands, a conductivity can obviously result only from jumps of electrons with a density $n \leqslant N_d \ll N_a$ between boron atoms. With increasing V_g, the value of n and thus that of σ increase. When the boron level intersects the Fermi level in the transition region between the ionized and neutral boron atoms (Fig. 1b), a new, additional channel for a hopping conductivity arises. In this case the product of the numbers of vacant and occupied impurity atoms reaches a maximum, so the conductivity does also. At $V_g \leqslant 0$, a surface enrichment channel arises, and σ increases. It is thus natural to assume that the flat-band condition holds near the minimum of the $\sigma(V_g)$ curve and that the electrical conductivity from the additional channel, σ_c, is the difference between the value of σ at the given value of the depleting voltage V_g and the conductivity at the point of the minimum, $\sigma_{\min}$: $\sigma_c = \sigma(V_g) - \sigma_{\min}$.

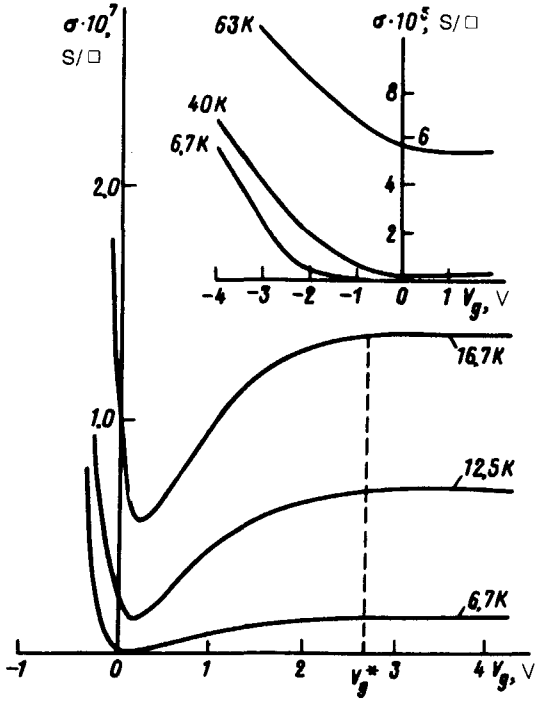

FIG. 2. Electrical conductivity of the layer of p-type Si versus the gate potential at various temperatures.

Figure 3 shows the temperature dependence $\sigma_{\min}(T)$ and $\delta_c(T)$ for values $V_g \geqslant 3$ V, at which we have $\sigma(V_g) = \text{const}$. A region with a constant activation energy $\epsilon = 9.5$ meV appears on the plot of $\sigma_{\min}(T)$. This activation energy is the same as that (ϵ_3) for the hopping conductivity in the interior of p-Si at the same doping level.[4] The plot of $\sigma_c(T)$ is also described by an activation law, but the activation energy satisfies $\epsilon_c \simeq 1.6$ meV $\ll \epsilon$, and this energy remains constant over the entire temperature range studied (in contrast with that for bulk samples, which exhibit a transition to a Mott law with decreasing temperature). We thus see that under these experimental conditions the conductivity involving states near the Fermi level is supported primarily by hops of electrons between nearest neighbors.[5] From the data in Fig. 3 it is a straightforward matter to estimate the width of the transition region, δ, which determines the conductivity σ_c. Under the assumption that in the limit $T \to \infty$ we have a ratio $\sigma_c/\sigma_{\min} \to \delta/d$, we find $\delta \simeq 50$ Å. This figure is close to the average distance between dopant atoms $R_a = \sqrt[3]{3/4\pi N_a} = 58$ Å.

The mechanism for a hopping conductivity by this additional channel can be described at a qualitative level as follows. At values of V_g above a certain threshold V_g^*, acceptors at the silicon surface are fully ionized, while those in the interior of the semiconductor are mostly neutral (Fig. 1b). At a nonzero temperature the electrons undergo thermally activated transitions from ionized boron atoms to the neighboring neutral acceptors which are above the Fermi level in a narrow transition layer (region III in Fig. 1b). This layer has a thickness δ. These electrons make an additional contribution to the current flowing along the surface of the sample. These transitions

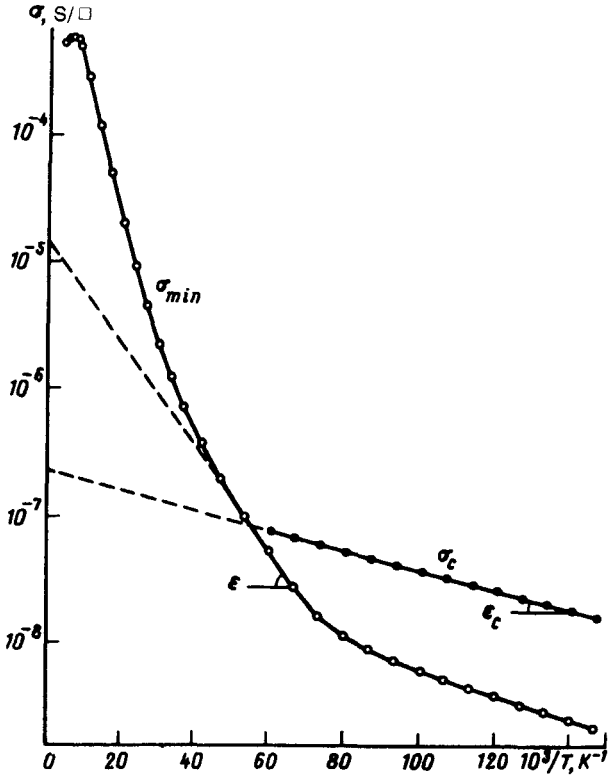

FIG. 3. Temperature dependence of $\sigma_{\min}$ and $\sigma_c=\sigma(V_g)-\sigma_{\min}$ for $V_g=3$ V.

are evidently accompanied by a displacement of electrons a distance $\simeq R_a$ into the interior of the Si, opposite the electric field of the space-charge region. These transitions are thus associated with a surmounting of the potential barrier of height $E_F R_a$, where E_F is the electric field of the space-charge region, in the region in which the boron level intersects the Fermi level. The activation energy for the hopping conductivity, ϵ_c, must therefore be $\simeq E_F R_a$.

Let us estimate the voltage V_g^*, at which this new hopping conductivity comes into play. Clearly, this new channel arises when the point at which the Fermi level intersects the boron level moves a distance $\geqslant R_a$ away from the surface. In this case the surface charge induced by the field effect, $Q = qN_aR_a$, corresponds to the potential of the field electrode, $V_g^* = qN_aR_a\kappa_0/4\pi d_0 \simeq 3$ V, in good agreement with the data in Fig. 2 ($\kappa_0 = 3.9$ is the dielectric constant of SiO_2).

To find the activation energy ϵ_c we need to find the electric field E_F. In the low-temperature limit ($T \to 0$), the electrons at boron atoms in slightly compensated silicon are known to be bound in 0-, 1-, and 2-complexes which include positively charged atoms of the compensating donors.[5] The Fermi level μ is below the level of the unperturbed boron impurity in this case: $\mu = \epsilon_3 = 0.61q^2/\kappa R_a$, where κ is the dielectric constant of Si. If $\mu < 0$, a positively charged donor cannot bind more than two electrons. The increase in the electron density due to the field effect is thus accompa-

nied by a conversion of 0- and 1-complexes into 2-complexes with a maximum concentration[6] N_d. In other words, at low temperatures the space-charge region is formed primarily by negatively charged 2-complexes, whose concentration increases to N_d as the bands become curved. This concentration then remains constant up to the point at which the boron level intersects the Fermi level (Fig. 1b). In the Schottky approximation we thus have $E_F = \sqrt{8\pi N_d \mu/\kappa} \simeq 2 \times 10^3$ V/cm and $\epsilon_c \simeq E_F R_a \simeq 1.2$ meV, in good agreement with the value of 1.6 meV found experimentally. We thus see that under the conditions of the field effect in Si:B there are manifestations of a concentration-induced transition to a conductivity with a constant hopping length involving states near the Fermi level. This conductivity is fundamentally different from the hopping conductivity in bulk semiconductors.[1,4,5] In particular, its activation energy is determined by the electric field of the space-charge region, rather than by randomly distributed charged centers. Another important distinction stems from the significant effect of the degree of compensation of the material, $K = N_d/N_a$, on ϵ_c [$\epsilon_c \simeq E_F R_a = R_a(8\pi N_d \mu/\kappa)^{1/2} \propto N_a^{1/3} K^{1/2}$]. In slightly compensaed bulk semiconductors, in contrast, ϵ_3 is essentially independent of K.

Near the minimum on the $\sigma(V_g)$ curves at $T < 20$ K, we are apparently seeing evidence of a second additional channel for a hopping conductivity involving states near the Fermi level. This channel is localized at the rear surface of the p-type layer, i.e., at the p–n junction (Fig. 1). Evidence for this conclusion comes from the tendency of ϵ (Fig. 3) to approach a constant value of approximately ϵ_c as the temperature is lowered.

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