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The 2D conducting system formed by nanocrystallites $CrSi_2$ in the (111) plane of silicon: New object

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HIGHLIGHTS

- The activation energy is lower than in the case of impurity condition.
- The carrier mobility is very high but it decreases rapidly with the growing temperature.
- The magnetoresistance is linear and decreases rapidly as the temperature rises.

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ABSTRACT

A conductivity quasi-two-dimensional system formed by nanocrystallites $CrSi_2$ located in the crystallographic (111) plane of silicon has been considered. At low temperatures the system exhibits several unique properties: (i) the activation energy in the temperature dependence of resistance is appreciably lower than in the case of impurity condition; (ii) the carrier mobility is very high but it decreases rapidly with the growing temperature; (iii) the magnetoresistance is linear and decreases rapidly as the temperature rises. To explain these features, a model has been proposed which assigns special importance to the charges at the nanocrystallites which appear due to the escape of the electrons to the conduction band (or holes to the valence band) of silicon.

The present technologies of materials for microelectronics have led to the advent of semiconducting single crystals in which impurity atoms are located within one crystallographic plane (the so-called δ-layers). These types of structures possess two-dimensional conductivity as in heterojunctions or inversion layers. Nevertheless, δ-layers were little used in microelectronics mainly because of the low mobility of the carriers subjected to frequent scattering at the ionized atoms in the δ-layer [1]. Meantime a structure in which one crystallographic plane of a high-energy-gap semiconducting crystal contains nanodimensional crystallites, rather than individual atoms, can exhibit new interesting and practically significant properties. These expectations were essentially supported while investigating the electron properties of an object containing chromic disilicide nanocrystallites in the crystallographic (111) plane of silicon. The chromic disilicide $CrSi_2$ is a low energy gap semiconductor (E_g=0.32 eV) [2] used in optical electronic IR elements, thermoelectric devices and so on.

The detailed description of the sample preparation and characterization is given in Ref. [3]. The sample was prepared as follows.[1] The p-type Si(111) wafer was used as the substrate. The native oxide and residual contaminants were removed from Si substrates' surface in the ultra high vacuum chamber by direct current annealing at 650–700 °C for 10–12 h, cooling during 12 h and finally by flashing at 1200 °C. Chromium was deposited from annealed Ta-tubes onto an atomically clean silicon Si(111)7 × 7 surface with a rate about 0.017 nm/min (~ 1 Å in terms of monolayer thickness). Silicon layers were deposited from sublimation silicon source made as the rectangular silicon plate, which is heated up with direct current flow. Silicon overgrowth with deposition rate of 3–4 nm/min was carried out by molecular beam

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epitaxy. The obtained crystal was annealed at $T=750\,^{\circ}$C to produce a solid-phase reaction. According to electron microscopy, the obtained samples contained small ($\sim$ 2–3 nm) and large (20–40 nm) $CrSi_2$ nanocrystallites; their heights being 2–4 nm. The average spacing between the small crystallites was $\sim$20 nm. The surface density was $\approx 2.5\times10^{11}$ cm^{-2} for the small nanocrystallites and $\approx 3\times10^{9}$ cm^{-2} for the large ones [4].

Such a sample possesses maximum permissible conduction anisotropy: at low temperatures it has no conduction in direction perpendicular to the plane with nanocrystallites and the conductivity is affected only through the plane containing nanocrystallites, i.e. it is actually the conductivity of a two-dimensional electron (hole) system.

We have investigated the temperature dependences of kinetic properties (resistance, magnetoresistance, and the Hall emf) in the interval 10–60 K. The sample with $CrSi_2$ nanocrystallites used for electric measurements was shaped as a double cross made of a narrow strip $\sim$ 1.5 mm wide and 9 mm long with aluminum contacts implanted into the $CrSi_2$ nanocrystallites rich layer by thermocompression. The measurements were performed at direct current. The magnetic field (up to 5 T) was excited with an automatic field-scan superconducting solenoid.

In the absence of magnetic field the observed temperature variations of the resistance ρ_{xx} exhibited the semiconducting type of behavior (Fig. 1). The dependences $\ln(\rho_{xx})$ vs. $1/T$ in Fig. 1 show to what extent the resistance variations follow the Arrhenius law in the course of activations in different temperature intervals:

$$\rho(T)=\rho_0\exp\left(\frac{E_i}{k_BT}\right). \tag{1}$$

We can separate three temperature intervals in which resistance, magnetoresistance and the Hall emf exhibit essentially different behavior. In region I (<20 K) the energy E_1 (solid line in Fig. 1) in Eq. (1) is very low ($\sim$ 0.9 meV at $I=10$ mkA). This suggests normal hopping conduction in this region: the electrons (or holes) localized near the nanocrystallites $CrSi_2$ jump between vacant states. Note that the hopping mechanism operates in the forbidden zone of silicon. The activation energy is $E_2=6.88$ meV in region II (20–40 K) (dashed line in Fig. 1) and decreases to $E_3=2.86$ meV (dotted line in Fig. 1) in region III (40–70 K).

These temperature intervals with strikingly low activation energies in terms of the Arrhenius law show that the transport of charge carriers is determined not only by thermal activation but also by a more complex process. It is surprising indeed that the activation energy E_3 in higher-temperature region III is significantly lower than the activation energy E_2 in low-temperature region II. Normally, the intensity of the activation process holds or even increases when the temperature rises.

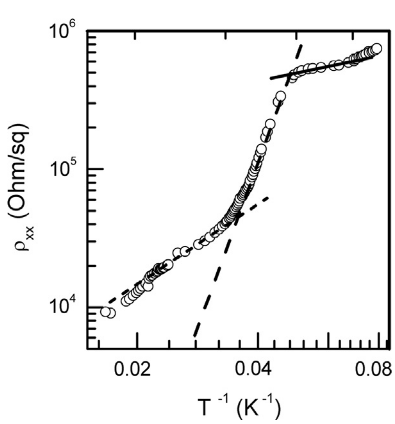

Fig. 1. The dependence of the sample resistance on opposite temperature T.

To obtain the temperature dependences of the carrier density n and mobility $\mu=e\tau/m^*$ (τ is the transport relaxation time, m^* is the effective mass), the Hall emf was measured at different temperatures. It was found that in all the cases the Hall emf changed linearly with the magnetic field. We could thus calculate the Hall constants for our two-dimensional system. The Hall constants, the carrier density n and the mobility μ were calculated within a two-dimensional model. In the equation for conductivity the parameters σ and n are related to unit area and the Hall constant is $R_H=U_{xy}/IB$, where I is the current and B is the magnetic field strength.

Note that the Hall constant of the investigated object varies in a very wide range: it decreases by three orders of magnitude (10^5–10^2 Ohm T^{-1}) as the temperature grows from 25 K to 60 K. The measured Hall constants show that the sample has hole conduction.

The parameters n and μ were calculated by standard equations for one type of carriers:

$$\sigma=ne\mu, \tag{2}$$

$$R_H=\frac{1}{ne}. \tag{3}$$

The density n is obtained from Eq. (3) and the mobility μ from Eq. (2) or from $\mu=\sigma R_H$. The dependences $n(T)$ and $\mu(T)$ are illustrated in Fig. 2a and b respectively. Note that the carrier mobility in region II is too high for such inhomogeneous sample.

Taking into account the dramatic temperature variations of the carrier mobility, the corresponding corrections must be made in the estimates of activation energy. For this purpose we can use the

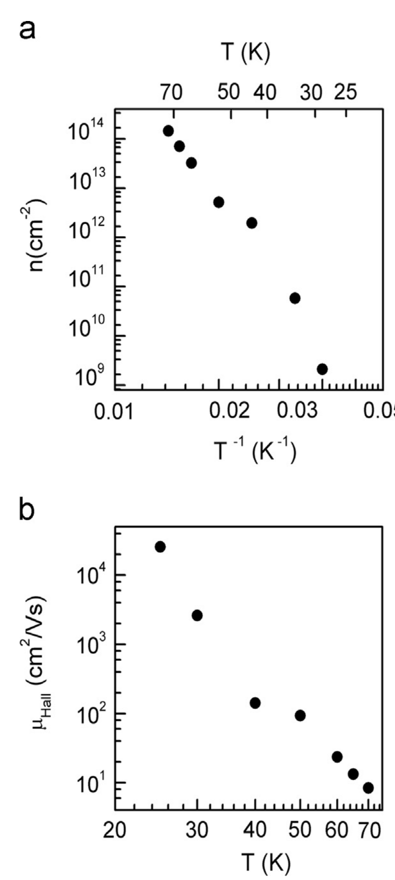

Fig. 2. The dependences of the carrier density n on T^{-1} (a) and the carrier mobility μ on $\ln(T)$ (b) (logarithmic scale along the ordinate axis).