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The galvanomagnetic properties of two-dimensional conducting systems formed by nanocrystallites $CrSi_2$ in the plane (111) of Si single crystals with a different type of conductivity

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The temperature dependences (in a range of 20 – 300 K) of the resistance, magnetoresistance (up to 5 T) and Hall electromotive force of silicon samples in which the chromium disilicide $CrSi_2$ nanocrystallites were arranged in plane (111) have been studied. Two samples which were prepared on silicon substrates with hole and electron conductivities were investigated. The transport properties of these systems are explained within the interhollow hopping band conductivity model. At T >50 K conductivity at the systems substantially depends on the characteristics of silicon.

Keywords: chromium disilicide, epitaxial silicon, the temperature dependence of the resistance.

Вивчена поведінка опору, магнітоопору (до 5 Тл) та э.р.с. Хола при зміні температури (в інтервалі 20 – 300 К) зразків кремнію, в яких в площині (111) розташовувалися нанокристаліти дисиліциду хрому $CrSi_2$. Вивчалися два зразки, що виготовлені на кремнії з дірковою та електронною провідністю. При низьких температурах транспортні властивості досліджених систем пояснені за допомогою запропонованої моделі «міжлункової» стрибкової зонної провідності. При температурах Т >50 К провідність систем додатково залежить від характеристик кремнію.

Ключові слова: дисиліцид хрому, епітаксійний кремній, температурна залежність опору.

Изучено поведение сопротивления, магнитосопротивления (до 5 Тл) и э.д.с. Холла при изменении температуры (в интервале 20 – 300 К) образцов кремния, в которых в плоскости (111) располагались нанокристаллиты дисилицида хрома $CrSi_2$. Изучались два образца, изготовленных на кремнии с дырочной и электронной проводимостью. При низких температурах транспортные свойства исследованных систем объяснены с помощью предложенной модели “межлуночной” прыжковой зонной проводимости. При температурах Т >50 К проводимость систем дополнительно зависит от характеристик кремния.

Ключевые слова: дисилицид хрома, эпитаксиальный кремний, температурная зависимость сопротивления.

Introduction

Transition metal silicides possess properties that in many respect attractive for applications in present-day microelectronics, optoelectronics and spintronics in particular [1, 2]. This is first of all due to their high compatibility with traditional silicon technologies [3]. Chrome disilicide ($CrSi_2$) is a low energy gap semiconductor ($E_g = 0.32$ eV) grown epitaxially on silicon of (111) orientation [4, 5].

$CrSi_2$/Si based heterostructures [6,7] are promising for development of thermoelectric transducers [8] and other electric instruments [9, 10]. Quantum points are the basic material of nanoelectonics, a rapidly progressing trend in microelectronics. Introduction of ultrasmall ordered quantum points, or nanocrystallites (NC), can lead (depending on the nature of clusters) to development of high-resolution LED screens and fast detectors. The optical and electrical properties of such nanostructures depend first of all on the density and the size of the introduced NCs, as well as the spacing between them in the nanocomposite layer. When investigating the transport properties of such systems, it is important to solve the problem of short-circuiting the NC layer by the substrate. In particular, it was shown [11] that after forming an atomic pure Si (111) 7×7 surface, the high-temperature annealing at T = 1250°C leads to appearance of a p-n junction on the Si n-type surface and the sign of the Hall voltage changes. Besides, a hole-enriched layer develops on the Si surface with the p-type conduction. The change in the dopant type at lowering temperature is also important [12]. The goal of the study was to investigate the influence of the type of conduction in the substrate on the transport properties of the $CrSi_2$ NC layer formed in the (111) plane of silicon.

Samples preparing

The technology of sample preparation was as follows [13]. A small quantity of Cr (~1 Å in terms of monolayer thickness) was short-time deposited on the (111) plane of silicon. The Cr-deposited face was then covered with an epitaxial Si layer. The crystal was annealed at 750 °C to conduct a solid-state reaction and to obtain a two-dimensional $CrSi_2$ layer of NCs in the Si matrix. The structure, the morphology and the optical properties of the NCs were investigated using transmission electron microscopy (TEM), atomic-force microscopy (AFM), ultraviolet photoelectron spectroscopy (UPS) and optical reflection spectroscopy (ORS). The formation of the $CrSi_2$ phase was controlled via UPS, ORS and TEM observations. The Cr distribution was investigated using the Rutherford backscattering (RBS) effect [14]. According to the electron microscopy data, the samples contained two types of $CrSi_2$ nanocrystallites: small (~ 3 nm) and large (20 – 40 nm). The height of the NCs was 2 – 4 nm. The average distance between the small crystallites was ~ 20 nm and their surface density was ≈ $2.5 \cdot 10^{11}$ cm^{-2}. The surface density of the large NCs was ≈ $3 \cdot 10^{9}$ cm^{-2}. The conduction in such a heterosystem proceeds in the plane containing crystallites and can be considered as the conduction of a two-dimensional system.

For a matrix crystal we used single crystal (111)-oriented Si plates. The boron doped Si plate with the resistivity 1 Ohm×cm (type SHB-1) was used to created sample with p-type substrate (sample A) and plates P-doped plate with resistivity 0.3 Ohm×cm (type SEP-0.3) used to created sample with n-type substrate (sample B).

Galvanomagnetic measurements were performed on samples of a Hall-bar configuration in the form of a narrow strip ~ 1.5 mm wide and ~ 9 mm long. The magnetic field up to 5 T was created with a superconducting solenoid with an automatic field scan. For these samples the temperature dependences of resistance, magnetoresistance and Hall emf taken at T = 20 – 300 K in magnetic fields up to 5 T have been investigated.

Results and discussion

The temperature dependences of samples resistance ρ_{xx} are illustrated in Fig. 1. They exhibit a semiconductive type of behavior.

The dependences of $\ln(\rho_{xx})$ on $1/T$ shown in Fig. 2 allows to estimate the fulfillment of the Arrhenius law [15]:

$$\rho_i(T) = \rho_0 \exp\left(\frac{E_i}{k_B T}\right), \qquad (1)$$

which describes the temperature variations of resistance in different temperature intervals. The temperature dependences in Fig. 2 are nonmonotonic and can be subdivided into three temperature intervals in which

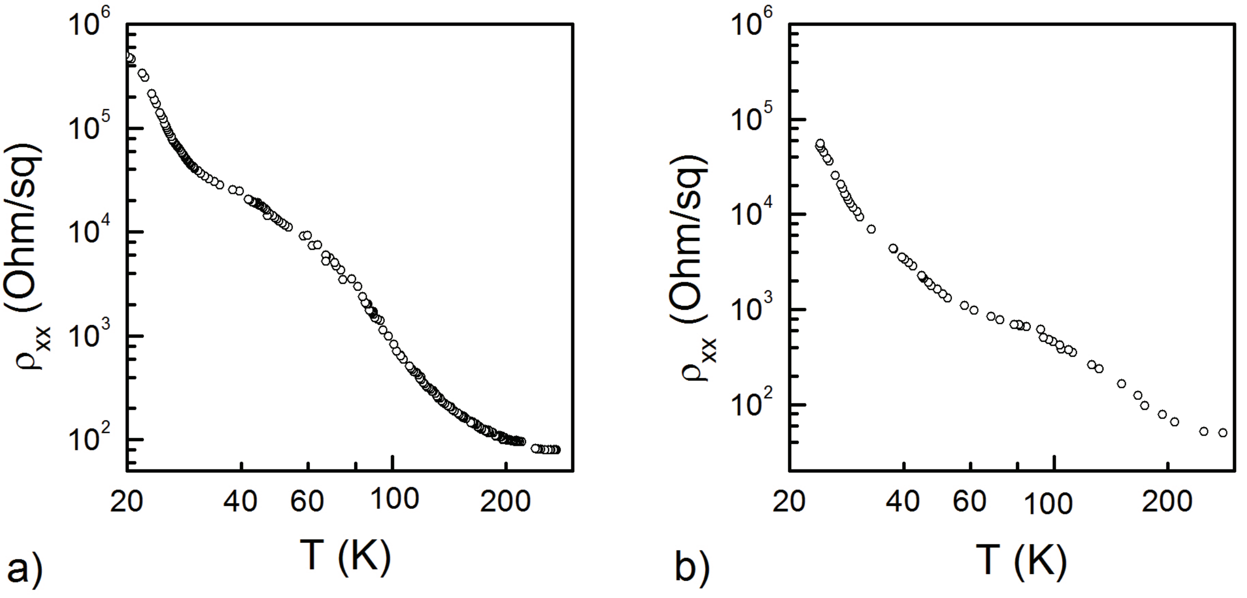

Fig.1. The temperature dependences of resistance of samples A (a) and (B).

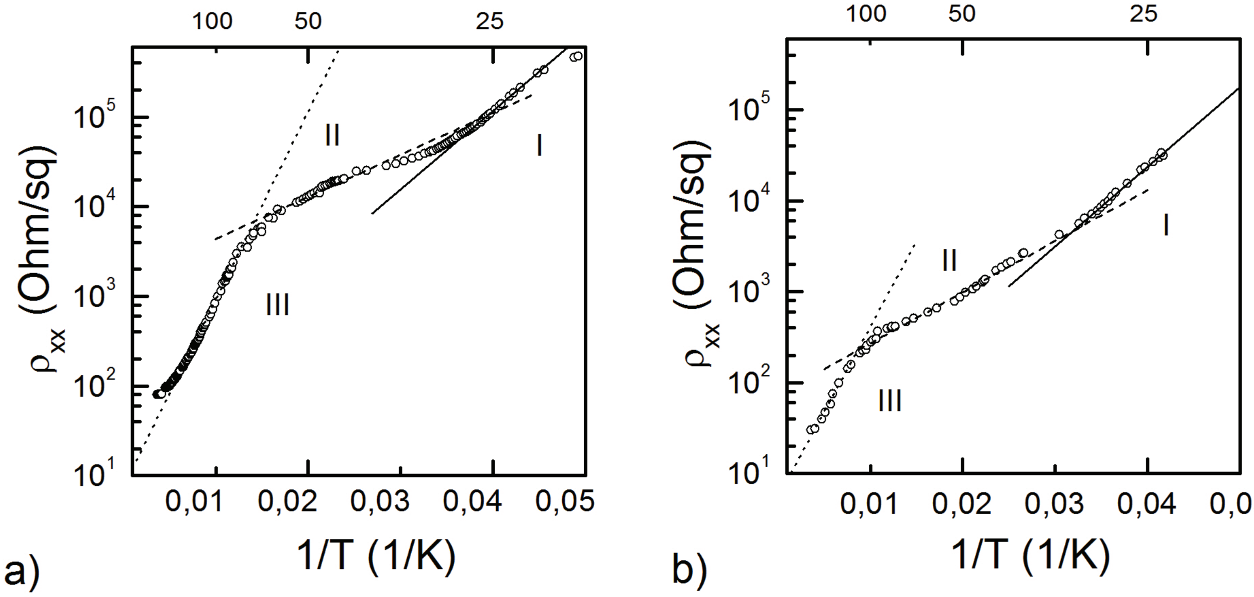

Fig. 2. The dependence of resistance of samples A (a) and (B) on inverse temperature. The straight lines are the calculation by Eq. (1) for the corresponding temperature interval.

resistance, magnetoresistance and Hall emf are distinctive in their behavior. In T-interval I (20 – 30 K) the energies E_I estimated from Eq. (1) are identical for both the samples: E_I = 15.5 meV. In this interval the conductivity is independent of the properties of the Si matrix and is realized only in the NC plane. The features of the temperature variations of resistance are interpreted within a proposed model of “interhollow” hopping conductivity [16].

Because of electric field and temperature influence, the electrons (holes) escape from the $CrSi_2$ nanocristallites located in one crystallographic Si plane, which deforms the energy spectrum of the semiconductive system in this plane. If the NCs are positively charged, hollows (cavities) are formed in the band conduction bottom. They are occupied by the electrons that escaped from the NCs or were activated from the valence band. If the NCs are negatively charged, they produce “antihollows” (bulges) in the valence band top where holes accumulate. The “hollows” and “antihollows” can be considered as quantum wells for electrons or holes in which carriers occupy the quantum dimensional states. In the electric field the charge carriers hop between the “hollows” and “antihollows”. It is particularly important that the hopping transition occurs in the conduction band for electrons or the valence band for holes. This transport can be concurrent with activation from the quantum level in a “hollow” or “antihollow”. The charges on NCs lead to reducing the distance from the valence band to the conduction band bottom, which, among other factors, may be responsible for the low activation energy, as compared to the order-of-magnitude higher activation energy in Si doped with impurities [15].

In T-interval I the magnetoresistance of the investigated samples varies practically linearly with the magnetic field (Fig. 3). The linear magnetoresistance can be explained in terms of the proposed hopping band mechanism as follows. In the perpendicular magnetic field the paths of the hopping holes are bent as a consequence of the cyclotron motion. The straight-line distance between the start and finish of a hop can be taken as an effective mean free path. The straight line is a chord of the cyclotron orbit and its length depends linearly on the cyclotron orbit radius. As the strength of the magnetic field grows, more and more holes hop to the nearest start region. As a result, the effective mean free path decreases linearly with the growing magnetic field strength, the temperature-dependent length of the cyclotron orbit are being unaltered. This cause a linear growth of the correction to the starting resistance, i.e., to a linear field-induced variation of magnetoresistance [16].

It is surprising that at the lowest temperatures (T-interval I) the samples exhibited very high values of magnetoresistance, which decreased rapidly the temperature rising.

The Hall component of magnetoresistance is linear in T-intervals I for both samples, which suggests a negligible contribution of the matrix crystal resistance to magnetoresistance in this temperature interval. The density n and the mobility μ of the charge carriers in T-interval I can be calculated using the following equations:

$$\mu = \sigma R_H \tag{2}$$

$$n = \frac{1}{R_H e}\ , \quad R_H = \frac{U_{xy}}{IB}, \tag{3}$$

where I is the current and B is the magnetic field strength.

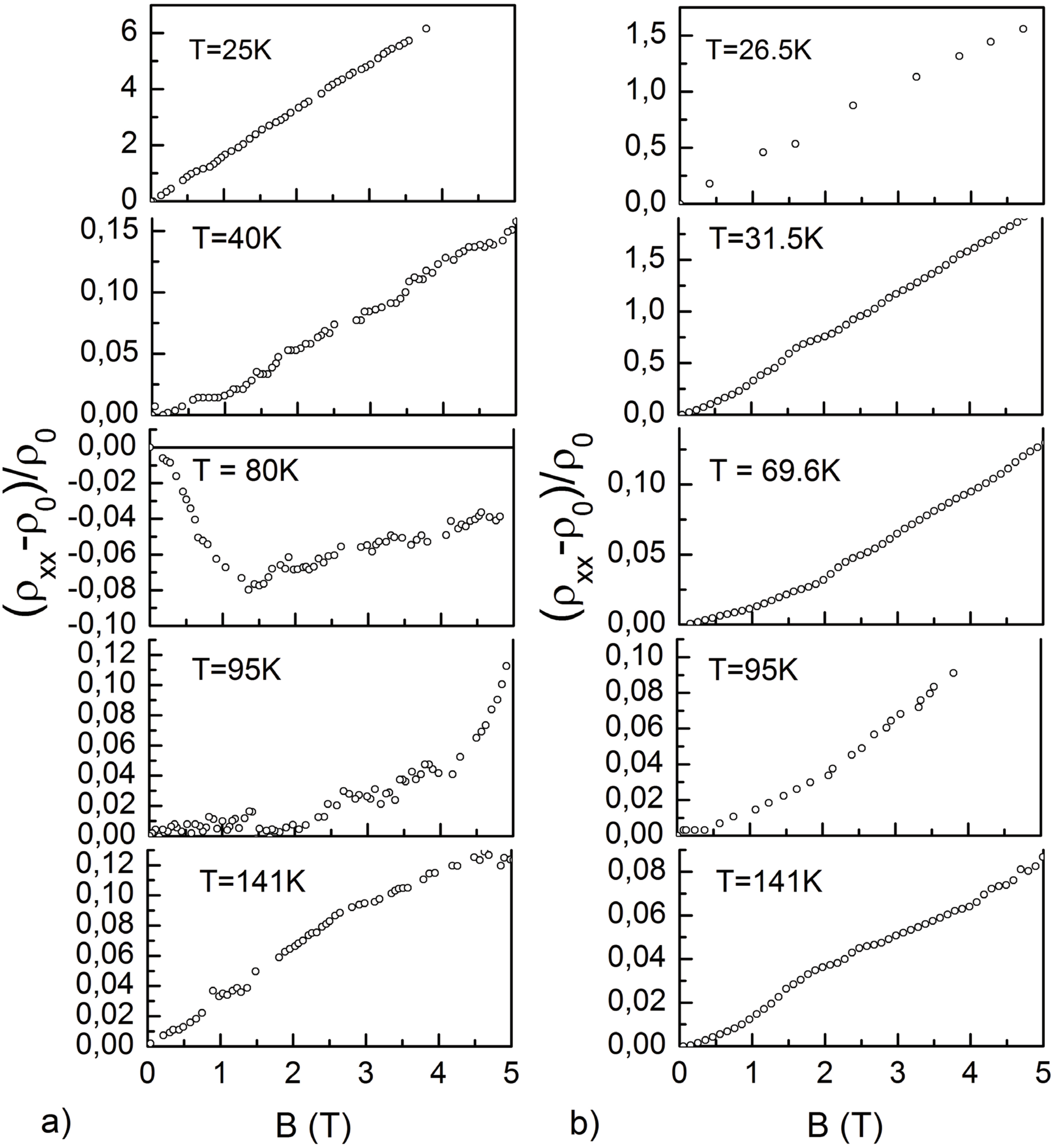

Fig. 3. The dependences of the reduced resistance of samples A (a) and (B) on the magnetic field.

It is found by Eq. (2) that in T-interval I carrier mobilities are very high both in samples A and B, which rather uncommon to inhomogeneous samples. The typical hopping mechanism is a process of charge carrier transitions between neighboring impurities and such hops proceed in the forbidden band of a semiconductor. As a result, the carrier mobility in the region of normal hopping conduction is rather low. In this case the hopping transport of electrons (holes) proceeds in the conduction band (or in the region near the top of valence band for holes), which affords a high carrier mobility.

At higher temperatures, in temperature diapasons T = 30 – 50 K (II) and T = 50 – 250 K (III), the temperature dependences of both samples are similar qualitatively but vary much quantitatively. For example, in T-interval II the activation energy E_2 = 9.4 meV for sample A and 11 meV for sample B, in T-interval III E_3 = 41.8 and 37.5 for sample A and B, respectively. Hence, in T-interval II the activation energy decreases as temperature rises. This is contrary to the normal activation process which should enhance and

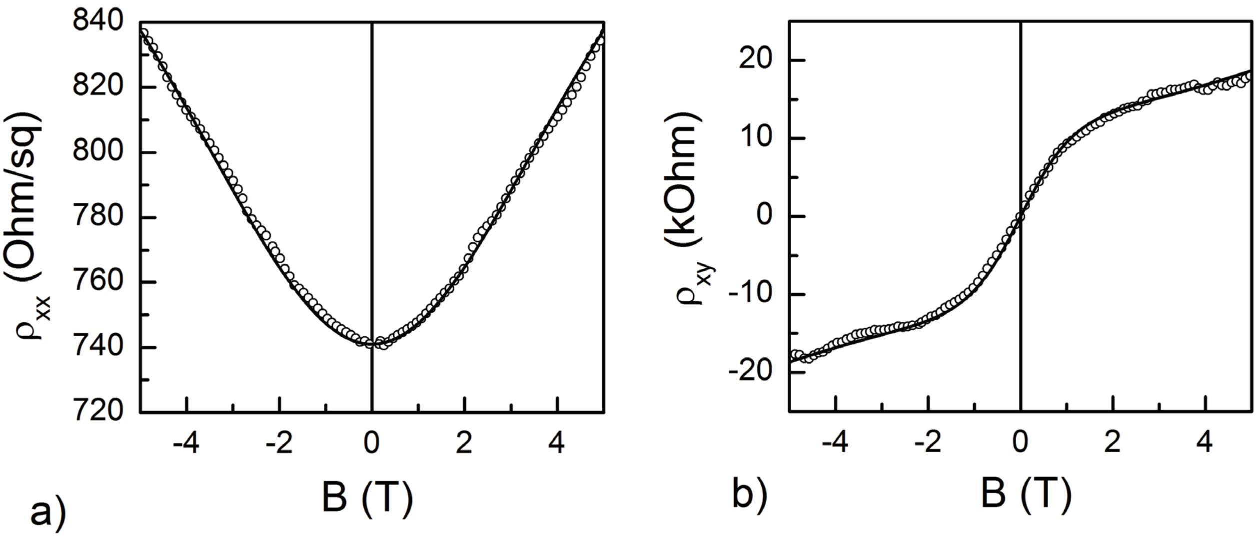

Fig. 4. The description of the longitudinal (a) and Hall (b) components of magnetoresistance of sample B (theory [17]) at T = 69.5 K.

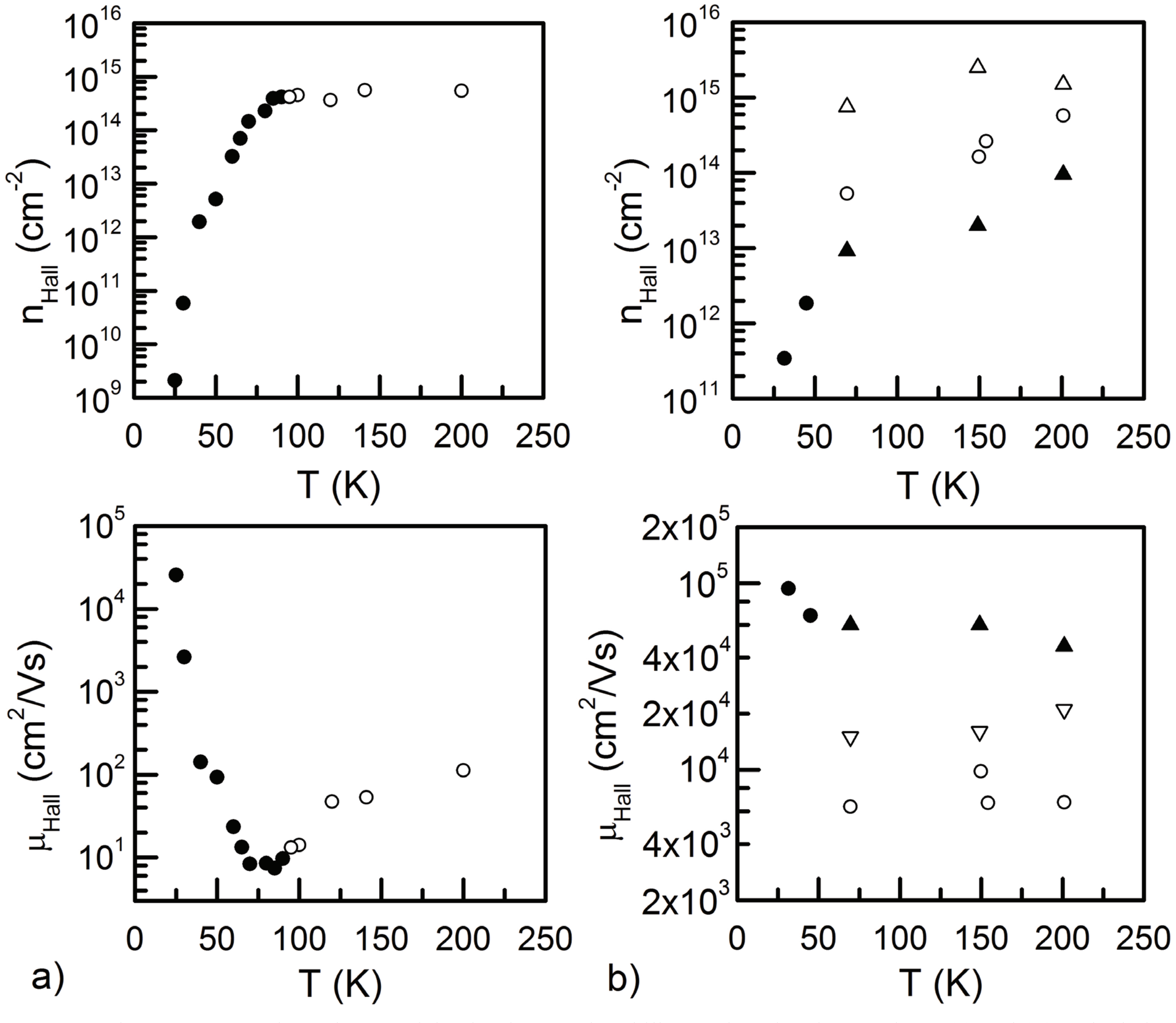

Fig. 5. The temperature dependences of the density n and mobility μ of carriers in samples A (a) and (B): calculation by Eqs. (2), (3) for temperature ranges I (●) and II, III (○); ▲ and △ – calculation by theory [17].

activation energy should grow as temperature rises. In the hopping conduction mechanism the energy *E* characterizes the average energy difference between the starting and final positions of the hopping electron and therefore sensitive to the topological features of the object.

The magnetic field dependences of resistance also vary significantly in these T-intervals (see Fig. 3). The character of the changes in the magnetoresistance of sample B (Figs. 3b, 4a) and the nonlinearity of the Hall component of magnetoresistance (Fig. 4b) suggest that the conduction properties of the matrix crystal are essential under these conditions and its mobile carriers create an additional channel bypassing conduction along the $CrSi_2$ NC layer. In this case the densities n_1, n_2 and the mobilities μ_1, μ_2 of the carriers in both conduction channels can be calculated using the theoretical model [17] which gives the magnetoresistance components in the semiclassical approximation:

$$\rho_{xx}(B)=\rho_0\left(1+\frac{rn_1n_2\mu_1\mu_2(\mu_1-\mu_2)^2B^2}{(n_1\mu_1+n_2\mu_2)^2+(rn_{Hall}\mu_1\mu_2)^2B^2}\right), \quad (4)$$

$$\rho_{xy}(B)=-\frac{\langle\mu^2\rangle+(r\mu_1\mu_2B)^2}{\langle\mu\rangle^2+(r\mu_1\mu_2B)^2}\frac{B}{n_{Hall}e}, \quad (5)$$

where $\rho_0=\frac{1}{(n_1\mu_1+n_2\mu_2)e}$ is the resistance in a zero magnetic field, $\langle\mu\rangle=\frac{n_1\mu_1+n_2\mu_2}{n_1+n_2}$ is the averaged mobility, *r* is dimensionless parameter characterizing the scattering between the conduction channels. If $r = 1$ Eqs. (4) and (5) turn to the expressions commonly used for noninteracting conducting channels. This model describes positive magnetoresistance which saturates as both the carrier groups progress to the condition of semiclassical strong magnetic field $\mu_iB > 1$. The description of the experimental dependences of magnetoresistance of sample B according to Eqs. (4) and (5) are illustrated in Fig. 4 (solid lines). We could thus calculate n_1, n_2, μ_1, μ_2 and the parameter *r*. The obtained characteristics of sample B are shown in Fig. 5 for the carriers of group 1 (solid triangles) and group 2 (empty triangles), $r = 1$. It may be concluded that the contributions of both channels to conduction are independent and additive.

The resistance of sample A responds to the magnetic field in a more complex way at the temperatures studied, including above all the regions with negative magnetoresistance in the range of T = 75 – 90 K. Negative magnetoresistance in the circumstances of variable-range hopping conduction was predicted in [18, 19] and observed in [20, 21]. Negative magnetoresistance can also be caused by localization of electrons in the impurity band near the hydrogen-like center. Hypothetically [22], a part of solitary impurity atoms can trap an extra electron and thus acquire a magnetic moment, the so-called localized spin. Localized spins and conduction electrons can develop an exchange interaction. It is possible that the spins of the interacting electrons are nonparallel and scattering can cause spin reorientation, i.e., an additional inelastic scattering mechanism can operate alongside the common mechanisms of scattering. In the external magnetic field spins line up with the field and the portion of the field-oriented spins increases as the field grows and the temperature lowers. Therefore, the inelastic mechanism of scattering operates as if it is partially switched off by the magnetic field, which suppresses the crystal resistance. A rise of the temperature causes spin disordering and the negative magnetoresistance effect changes to the positive one. Unfortunately, it is impossible to separate the contributions to conduction made by carriers located in the $CrSi_2$ NC plane and in the matrix crystal.

Conclusion

The transport properties of two samples in which the chromium disilicide $CrSi_2$ nanocrystallites were arranged in silicon plane (111) with hole and electron conductivities were investigated. For this the temperature dependence (in the range of 20 – 300 K) of the resistance, magnetoresistance (up to 5 T) and Hall electromotive force was experimental get and study.

It was found, that studied samples conductivity has complicated character, this is shown in singularity of experimental temperature dependencies of samples resistance.

It was discovered, that studied samples exhibit very high mobility of the carriers at low temperatures (~ 10^5 $cm^2V^{-1}s^{-1}$).

Another feature of this object is the giant linear magnetoresistance appearing at low temperatures.

At low temperatures the unusual properties are interpreted within a proposed model of "interhollow" hopping band conduction implemented in 2D systems created by chromium disilicide $CrSi_2$ nanocrystallites arranged in plane (111) of silicon matrix. At T > 50 K systems conductivity substantially depends on the characteristics of silicon.

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