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Piezoresistive properties of boron-doped silicon whiskers at cryogenic temperatures

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Piezoresistive properties of boron-doped *p*-type silicon whiskers in temperature range of 1.7 to 300 K were studied. The giant piezoresistance was observed in *p*-Si whiskers in the vicinity of metal-insulator transition at helium temperatures. The gauge factor dependence on impurity concentration and temperature has been investigated. The extremely high gauge factor $5.7 \cdot 10^5$ at 4.2 K has been found in moderately doped silicon microcrystals with boron concentration $3 \cdot 10^{18}$ cm^{-3} in the vicinity of metal-insulator transition at the insulating side. The possibility of application of giant piezoresistance to develop high-sensitive mechanical sensors operating, at cryogenic temperatures is discussed.

Исследованы пьезорезистивные свойства нитевидных кристаллов кремния, легированных бором, в диапазоне температур 1,7–300 К. Гигантский пьезорезистивный эффект в нитевидных кристаллах *p*-Si наблюдался вблизи перехода металл-изолятор при гелиевых температурах. Исследовалась зависимость коэффициента тензочуствительности от концентрации примеси и температуры. Экстремально высокий коэффициент тензочувствительности $5{,}7 \cdot 10^5$ при 4,2 К был обнаружен в микрокристаллах кремния с промежуточным уровнем легирования с концентрацией бора $3 \cdot 10^{18}$ см$^{-3}$ вблизи перехода металл-изолятор со стороны изолятора. Обсуждается возможность использования гигантского пьезосопротивления для создания высокочувствительных сенсоров механических величин, работоспособных при криогенных температурах.

Silicon microcrystals grown in form of whiskers, due to their perfect crystalline structure and high mechanical strength combined with versatile and inexpensive technology, are a model material of good prospects to study the piezoresistance effect in silicon in the wide temperature range, including the cryogenic temperatures. At the same time, silicon whiskers are an ideal material to design piezoresistive mechanical sensors [1, 2]. It is known that a giant pizoresistance may be observed in doped semiconductors at cryogenic temperatures when the electrical conductance is due to hopping between the localized or partially localized impurity states [3]. The effect of uniaxial mechanical strain (compression) on the extrinsic conduction of silicon at cryogenic temperatures was described in [4]. The hopping conduction in uniaxially stressed boron-doped silicon near metal-insulator transition (MIT) in the temperature range 0.05–0.75 K has been studied [5]. But in that paper, there is no information about the piezoresistance effect in doped silicon near MIT at cryogenic temperatures.

Our studies of the complex behavior of silicon whiskers moderately and heavily doped with boron at concentrations slightly lower than the critical concentration of the metal-insulator transition (MIT) led to observations of very high piezoresistance at 4.2 K. The estimated gauge factor (GF) value was found to be of about $(1-2) \cdot 10^4$ at 4.2 K [6].

Table. Thermal strain of silicon whiskers mounted on substrates

Substrate	$T = 4.2$ K	$T = 20$ K	$T = 77$ K	$T = 300$ K
Copper	$-3.81 \cdot 10^{-3}$	$-3.80 \cdot 10^{-3}$	$-3.63 \cdot 10^{-3}$	$-1.60 \cdot 10^{-3}$,
Melted quartz	$4.74 \cdot 10^{-4}$	$4.70 \cdot 10^{-4}$	$4.48 \cdot 10^{-4}$	$2.66 \cdot 10^{-4}$

This is approximately two orders higher then a conventional gauge factor in p-type Si being of order $GF = 100$. The purpose of this work is to study the piezoresistive properties of boron doped Si whiskers at cryogenic temperatures to reveal the doping level where the maximum piezoresistance could be observed, as well as to study the temperature behavior of gauge factor.

Silicon whiskers (SW) were grown by chemical transport reactions in a closed system with Br as transport agent [7]. SW growed as elongated regular hexagonal prisms with the side face width between a few microns and a few tens of microns. The longitudinal axis of the crystals corresponds to the [111] crystallographic direction. This direction corresponds to the maximal longitudinal piezoresistance in p-type silicon. Therefore the whiskers were doped during their growth with boron at concentrations of $8 \cdot 10^{17}$ to $1 \cdot 10^{19}$ cm^{-3}. The presence of gold and platinum as growth initiating impurities provided some compensation of acceptor impurity. For experimental studies, 3–5 mm long whiskers with the side face width of about 20–30 μm were selected. Electrical contacts to the crystals were fabricated by welding of Pt microwire.

The piezoresistive properties of Si whiskers were studied in the temperature range from 1.7 to 300 K. Because of the whisker small dimensions and specific shape, a special technique of straining during experimental measurements was elaborated. Due to the small dimensions and specific shape of Si whiskers, it was impossible to apply a mechanical loading directly thereto. Therefore, the experiments on piezoresistance were performed with samples mounted on specially manufactured substrates. In this case, the sample undergoes a thermal strain ε_t, arising due to the difference in thermal expansion coefficients of the sample and the substrate material. This thermal strain ε_t could be estimated in the isotropic approximation as [8]

$$\varepsilon_t(T) = \gamma\int_{T_0}^{T}[\alpha_s(T) - \alpha_c(T)]dt, \tag{1}$$

where $\alpha_s(T)$ and $\alpha_c(T)$ are the thermal expansion coefficients of the substrate and the sample, respectively; T_0, the hardening temperature of adhesive that was used for mounting the whiskers on substrate. The dimensionless factor γ characterizes the strain transmission from the substrate to the sample. The γ value was determined theoretically and experimentally in [9], it equals 0.7. The estimated $\varepsilon_t(T)$ values for Si whiskers mounted on different substrates are presented in Table. Thus, the mounting of Si whiskers on selected substrates provides the tensile (on quartz substrate) and compressive (on Cu substrate) strain of these crystals.

The gauge factor of Si microcrystals and its temperature dependence were calculated from experimental data on resistivity vs. temperature of free (unstrained) and strained crystals. Gauge factor was estimated as

$$K = (\rho - \rho_0)/(\rho_0 \times \varepsilon), \tag{2}$$

where ρ_0 is the electrical resistivity of unstrained crystals; ρ, that of strained crystal; ε, the uniaxial strain applied to the crystal. The resistivity of Si whiskers was determined from the resistance of microcrystals and their geometrical dimensions, that were determined by microscopy. During the experiment, resistance of crystals was measured by digital device with automatic data registration by computer. The data of temperature sensor mounted near the investigated crystal were registrated simultaneously. The experiments with Si whiskers at cryogenic temperatures were carried out in International Laboratory of High Magnetic Fields and Low Temperatures in Wroclaw, Poland.

For piezoresistive investigation, selected were silicon whiskers with different boron concentrations corresponding both to the metallic and insulating sides of metal-insulator transition (MIT). Taking into account that critical boron concentration in silicon corresponding to MIT, is $N_c = 5 \cdot 10^{18}$ cm^{-3}

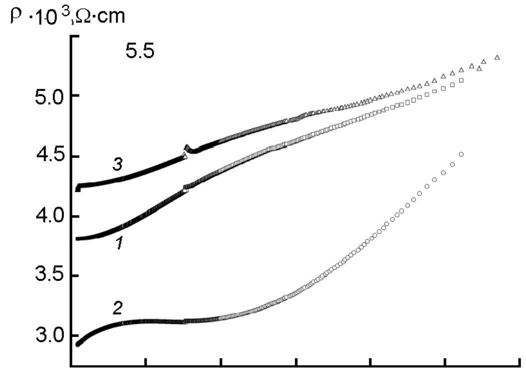

Fig. 1. Temperature dependences of the resistivity for *p*-type Si whiskers from Si:B1 set, free (*1*, unstrained) and under compressive (*2*) and tensile (*3*) strains.

[4], the presented experimental sets selected by boron doping form a logical sequence: samples from Si:B1 set with $N_B = 1{\cdot}10^{19}$ cm^{-3} show the typical metallic conductivity, the samples from sets Si:B2 with $N_B = 7{\cdot}10^{18}$ cm^{-3} and Si:B3 with $N_B = 5.5{\cdot}10^{18}$ cm^{-3} are on the MIT metallic side, whereas the samples from sets Si:B4 with $N_B = 3{\cdot}10^{18}$ cm^{-3} and Si:B5 with $N_B = 8{\cdot}10^{17}$ cm^{-3} are on the MIT insulating side. Samples from Si:B3 and Si:B4 sets are in the vicinity of MIT. In Fig. 1, 3, 5, are presented are examples of the experimental results obtained, that is, the temperature dependences of resistivity for free (unstrained) microcrystals and for crystals mounted on substrates. Corresponding temperature dependences of gauge factor calculated from equation (2) are shown in Fig. 2, 4, 6.

Microcrystals of the most doped Si:B1 set manifest a typical metallic temperature dependence of resistivity, monotonous in the whole temperature range from 4.2 to 300 K with a positive temperature coefficient of resistivity (TCR) (Fig. 1). Piezoresistance of these samples is also monotonous and "classic" one (cf. curves 2 and 3 for strained samples with curve 1 in Fig. 1). This means that the gauge factor of these crystals depends slightly on temperature and has positive sign for both tensile and compressive strain (see Fig. 2). For microcrystals from Si:B2 set where boron density corresponds to metallic side of MIT, we observed that high compressive strain from the copper substrate at cryogenic temperatures "turns" the sample into the critical MIT region where the negative sign of gauge factor is observed. This means that in this case, the microcrystal resistivity increases at compressive strain in spite of classical Smith's piezoresistance, when resistivity of *p*-Si decreases at compressive strain [10].

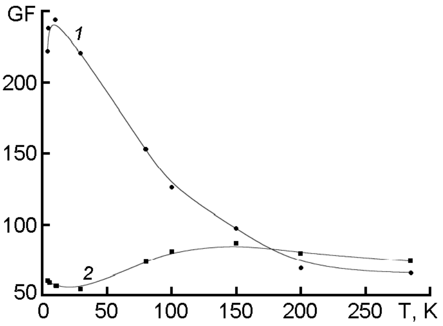

Fig. 2. Gauge factor of *p*-Si whisker from Si:B1 set vs. temperature under tensile (*1*) and compressive (*2*) strains.

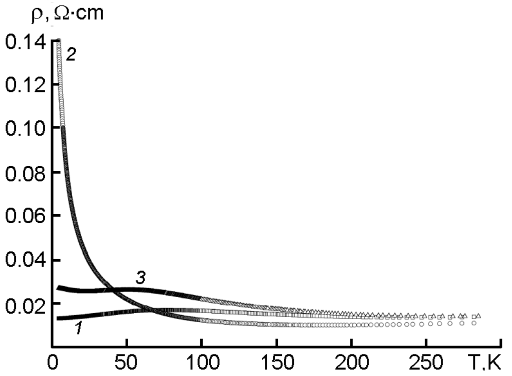

Fig. 3. Temperature dependences of the resistivity for *p*-type Si whiskers from Si:B3 set, free (*1*, unstrained) and under compressive (*2*) and tensile (*3*) strains.

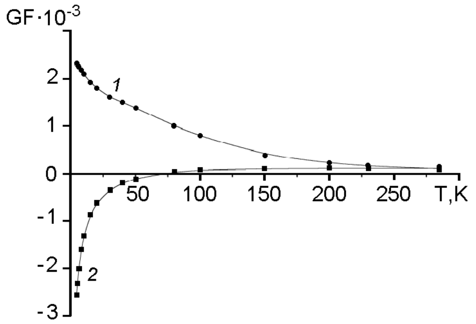

Fig. 4. Gauge factor of *p*-Si whiskers from Si:B3 set vs. temperature at tensile (*1*) and compressive (*2*) strains.

The microcrystals from Si:B3 set are the most close to the MIT at the metallic side thereof. The metallic temperature behavior of the "free" sample (Fig. 3, curve 1) under tensile strain from quartz substrate becomes closer to the insulating samples with negative TCR at helium temperatures (Fig. 3, curve 3). A high compressive strain from

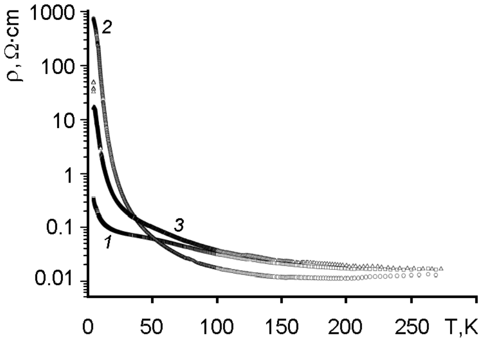

Fig. 5. Temperature dependences of the resistivity for *p*-type Si whiskers from Si:B4 set, free (*1*, unstrained) and under compressive (*2*) and tensile (*3*) strains.

the copper substrate transforms this sample into an insulating one (Fig. 3, curve 2). Temperature dependences of the gauge factor for such microcrystals calculated from the experiments on substrates are presented in Fig. 4. At liquid helium temperature, the gauge factor is $GF \approx 2.3 \cdot 10^3$ for tensile strain and $GF \approx -2.6 \cdot 10^3$ for compressive strain. Si microcrystals from Si:B4 set behave as insulators in the whole temperature range (Fig. 5), remaining close to the MIT. The strains from substrates change very effectively the resistivity of crystals at cryogenic temperatures. Even a elatively small tensile strain from the quartz substrate ($4.7 \cdot 10^{-4}$ relative units) increases the resistivity by factor ca. 100 at 4.2 K, while compressive strain from the copper substrate ($-3.8 \cdot 10^{-3}$ relative units) causes a dramatic rise of resistivity by ca. 2170 times. This is really a giant piezoresistance. The gauge factor for these samples attains at 4.2 K $GF \approx -5.7 \cdot 10^5$ for compressive strain and $GF \approx 3 \cdot 10^5$ for tensile strain (Fig. 6).

A further decrease of impurity concentration in microcrystals does not result in any increase of gauge factor at cryogenic temperatures. Samples of Si:B5 set show the typical insulating temperature behavior of resistivity. The $\rho(T)$ dependence is not changed qualitatively after mounting on substrates and changes relatively slightly quantitavely as compared to microcrystals from Si:B4 set. The temperature dependence of gauge factor $GF(T)$ for these crystals has an extremum in the temperature range 15 to 25 K near the critical temperature of metal-insulator phase transition; at 4.2 K, the non-classical piezoresistance of these crystals becomes small. The maximum gauge factor value for these samples attains $GF = -3600$ for compressive strain and 3700 for tensile strain.

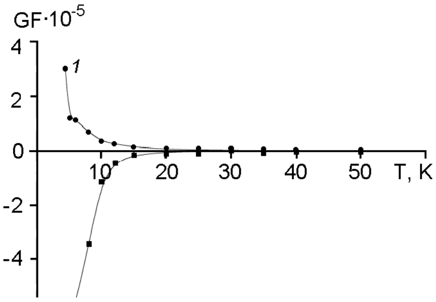

Fig. 6. Gauge factor of *p*-Si whisker from Si:B4 set vs. temperature under compressive (*1*) and tensile (*2*) strains.

Consideration of temperature dependences of the gauge factor for *p*-type silicon whiskers confirms the non-classic piezoresistance at cryogenic temperatures near the metal-insulator transition. This effect becomes a giant one at helium temperatures for Si with boron concentration $N_B = 3 \cdot 10^{18}$ cm^{-3} at the insulating side of MIT (see Fig. 6). Such a non-classic piezoresistance has a special feature: both under tensile and compressive strain, the crystal resistivity behaves similarly, i.e. it increases as the applied strain rises. Therefore, at cryogenic temperatures, in crystals from Si:B2–Si:B5 sets we observed the positive sign of gauge factor at tensile strain and negative sign of gauge factor at compressive strain.

Silicon whiskers with a giant gauge factor could be applied as piezoresistors in mechanical sensors operating at cryogenic temperatures. The main disadvantage of this application is strong temperature dependence of the giant gauge factor. Therefore, the most advisable application of such piezoresistors is the development of mechanical sensors for fixed cryogenic temperatures (liquid helium, liquid hydrogen). The successful application of boron-doped Si microcrystals with $GF - (1\text{–}2) \cdot 10^4$ in pressure sensors at 4.2 K has been considered in [6]. Heavily doped Si whiskers from Si:B1 set with metallic type conductivity, which demonstrate the classic piezoresistance, could be applied in mechanical sensors operating in wide temperature range of 4.2 to 300 K.

Thus, a giant piezoresistance at helium temperatures has been observed in *p*-type silicon whiskers at boron concentrations near the metal-insulator transition. At boron concentration of $N_B = 3 \cdot 10^{18}$ cm^{-3}, we found the maximum gauge factor $GF = -5.7 \cdot 10^5$ at

4.2 K. This corresponds to the relative change of resistivity $\rho(\varepsilon)/\rho_0 \approx 2170$. The less doped samples show a distinct maximum in $GF = f(T)$ dependence; the position of this maximum depends on the doping concentration and strain level. Heavily doped *p*-Si whiskers ($N_B = 1 \cdot 10^{19}$ cm^{-3}) with metallic type conductivity showed the classic piezoresistance at cryogenic temperatures. The Si whiskers with a giant gauge factor could be applied to design high-sensitive piezoresistive mechanical sensors (strain gauges, pressure sensors and level sensors) operating at fixed cryogenic temperatures, e.g. in cryogenic liquids, such as liquid helium and liquid hydrogen. Heavily doped Si microcrystals with classic piezoresistance could be successfully used in mechanical sensors operating in the wide temperature range of 4.2 to 300 K.

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П’єзорезистивні властивості легованих бором ниткоподібних кристалів кремнію при кріогенних температурах

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Досліджено п’єзорезистивні властивості ниткоподібних кристалів кремнію, легованих бором, в діапазоні температур 1,7–300 К. Гігантський п’єзорезистивний ефект у ниткоподібних кристалах *p*-Si спостерігався поблизу переходу метал-ізолятор при гелієвих температурах. Досліджено залежність коефіцієнту тензочутливості від концетрації домішок і температури. Екстремально високий коефіцієнт тензочутливості $5{,}7 \cdot 10^5$ при 4,2 К був знайдений у мікрокристалах кремнію з проміжним рівнем легування з концентрацією бору $3 \cdot 10^{18}$ см$^{-3}$ поблизу переходу метал-ізолятор з боку ізолятора. Обговорюється можливість використання гігантського п’єзоопору для створення високочутливих сенсорів механічних величин, працездатних при кріогенних температурах.