Strain induced effects in p-type silicon whiskers at low temperatures

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Complex studies of strain induced effects in boron doped *p*-type silicon whiskers with [111] crystallographic direction in the wide temperature range 4.2 – 300 K at magnetic fields up to 14 T and under high-energy electron irradiation were carried out. The peculiarities of piezomagnetoresistance of Si whiskers heavily boron doped and with boron concentration in the vicinity of metal-insulator transition were determined. The influence of electron irradiation with energy 10 MeV and fluence $\Phi = 5\cdot10^{17}$ el/cm^2 on the gauge factor of boron doped Si whiskers at low temperatures have been also studied. High-sensitive piezoresistive sensor to measure pressure of liquid helium on the basis of silicon whiskers with a giant gauge factor was developed. Heavily doped Si whiskers with classic piezoresistance have been successfully used in mechanical sensors operating in the wide temperature range 4.2 – 300 K.

Проведены комплексные исследования деформационно-стимулированных эффектов в нитевидных кристаллах (НК) кремния *p*-типа, легированных бором, с кристаллографической ориентацией <111> в интервале температур 4,2–300 К и магнитных полях до 14 Тл, облученных электронами высоких энергий. Обнаружены особенности пьезомагнитосопротивления в сильнолегированных бором НК Si и с концентрацией бора вблизи перехода металл-изолятор при низких температурах. Изучено также влияние электронного облучения с энергией 10 МеВ и флюэнсом $\Phi = 5\cdot10^{17}$ эл/см^2 на коэффициент тензочувствительности НК Si, легированных бором, при низких температурах. Разработан высокочувствительный пьезорезистивный сенсор для измерения давления жидкого гелия на основе нитевидных кристаллов кремния с гигантским коэффициентом тензочувствительности. Сильнолегированные НК Si с классическим пьзосопротивлением успешно используются в сенсорах механических величин для широкого интервала температур 4,2 – 300 К.

1. Introduction

Extensive studies devoted to semiconductor whiskers, particularly, silicon whiskers, are carried out due to their high structural perfection and special morphology. The structural perfection of whiskers results in their excellent mechanical properties, consequently *p*-type Si whiskers are successfully used in mechanical sensors of various applications [1, 2].

Low temperature studies of strain-induced effects in *p*-type silicon whiskers are actual both to study physical properties of crystals and to estimate the creation possibility of mechanical sensors based on these crystals operating at low temperatures. Metal-insulator transition (MIT) at low temperatures is the best condition for the clearest revelation of strain-induced effects peculiarities in doped semiconductors. To extend the functional possibilities of piezoresistive mechanical sensors based on boron doped silicon whiskers it is necessary to carry out the complex studies of strain induced effects in these crystals in the wide temperature range 4.2 – 300 K at high magnetic fields and under electron irradiation.

2. Experimental procedure

Silicon whiskers were grown by chemical transport reactions in a closed bromine system. The longitudinal axis of the crystals corresponds to [111] crystallographic direction. There were studied silicon whiskers with different boron doping: 1) heavily doped crystals with metallic conductivity; 2) in the vicinity of MIT from the metallic side and 3) in the vicinity of MIT from the insulating side. The contacts to the crystals were fabricated by welding of Pt microwire.

Silicon whiskers were strained by mounting them on the specially selected substrates with a thermal expansion coefficient different from that of silicon. Details of such experimental method, including the thermal strain estimation of Si whiskers for different substrates, were reported in [3]. Copper and quartz substrates were used to achieve uniaxial compressive ($\varepsilon = -3.8\cdot10^{-3}$ r.u.) qand tensile strain ($\varepsilon = 4.7\cdot10^{-4}$ r.u) at 4.2 K, correspondingly. Thermal strain of silicon whiskers in [111] direction in the whole studied 4.2 – 300 K temperature range was calculated.

The low temperature measurements of Si whiskers piezoresistance at high magnetic fields up to 14 T have been carried out by cooling the crystals down to 4.2 K using helium cryostat in the International Laboratory of High Magnetic Fields and Low Temperatures in Wroclaw, Poland. Irradiation of silicon whiskers by electrons with energy 10 MeV and fluence $\Phi = 1\cdot10^{17} - 1\cdot10^{18}$ el/cm^2 at room temperature was carried out by the impulse electron accelerator Microtron M-30 [4].

The temperature dependences of resistivity for unstrained and strained (mounted on substrates) doped silicon whiskers were studied in the temperature range 4.2 – 300 K in [5]. The gauge factor of Si whiskers and its temperature dependences were calculated from resistivity vs. temperature experimental data for unstrained and strained crystals. Gauge factor was estimated as

$$GF = (\rho - \rho_0)/(\rho_0 \cdot \varepsilon), \qquad (1)$$

where ρ_0 and ρ is the resistivity of unstrained and strained crystal, correspondingly, ε — uniaxial strain, applied to the crystal.

3. Results and discussion

It is known that a giant piezoresistance is observed in doped semiconductors at low temperatures when electrical conductivity is due to carriers hopping on localized impurity states [6]. The effect of uniaxial strain on the conductivity of silicon at cryogenic temperatures was described in [7]. Strain induced metal-insulator transition was observed in heavily doped *n*-type Si crystals at 4.2 K [8]. The hopping conduction in uniaxially strained silicon doped by boron in the vicinity of MIT in the temperature range 0.05 – 0.75 K has been also studied [9], but there is no information about the magnitude of piezoresistance at cryogenic temperatures.

The experimental results of gauge factor measurement for Si whiskers with different boron doping level in the temperature range 4.2 – 300 K are presented in [5]. The classic piezoresistance was observed in heavily doped *p*-type Si whiskers (ρ_{300K} = 0.006 Ohm·cm) at cryogenic temperatures: the gauge factor has positive sign and equals $GF = 60$ at 4.2 K for both tensile and compressive uniaxial strains. The non-classic piezoresistance at cryogenic temperatures was revealed in silicon whiskers with ρ_{300K} = 0.011 Ohm·cm (in the vicinity of MIT from the metallic side), and the gauge factor has negative sign for compressive strain

Table. The graduating characteristics at 4.2 K of developed pressure sensors based on *p*-type Si whiskers with different resistitity

Pressure, MPa	0	2	4	6	8	10
U, mV ρ_{300K} = 0.006 Ohm·cm	0	18.2	36.4	54.6	72.8	91
U, mV ρ_{300K} = 0.014 Ohm·cm	0	17	50	105	217	430

and equals $GF = -2.6 \cdot 10^3$ at 4.2 K. The most obvious non-classic piezoresistance was revealed in Si whiskers with ε_{300} K = 0.013 Ohm·cm (in the vicinity of MIT from the insulating side), their gauge factor achieves $GF = -5.7 \cdot 10^5$ at temperature 4.2 K for uniaxial compressive strain and $GF \approx 3 \cdot 10^5$ for tensile strain. The carried studies [5] gave the possibility to develop high-sensitive mechanical sensors based on p-Si whiskers with boron concentration in the vicinity of MIT operating at low temperatures. The heavily doped silicon whiskers due to the best combination of gauge factor and temperature stability could be used to create mechanical sensors, operating in the wide temperature range 4.2 – 300 K.

Effect of uniaxial strain on magnetoresistance was studied mainly for n-type germanium and silicon crystals [8]. The paper devoted to studies of longitudinal magnetoresistance of p-type Si at magnetic fields up to 350 kE under uniaxial strain appeared only recently [10]. But these studies were carried out on silicon with large resistivity (from 10 to 2200 Ohm·cm) at 77 K. Therefore it is interesting to study the effect of uniaxial strain on magnetoresistance of p-type silicon whiskers heavily doped and with boron concentration in the vicinity of MIT at high magnetic fields up to 14 T and liquid helium temperature.

The obtained experimental results of transverse magnetoresistance studies of Si whiskers with boron concentration in the vicinity of MIT for unstrained crystals (curves *1*) and under uniaxial compressive strain in direction [111] (curves *2*) at temperature 4.2 K are shown in Fig. 1.

The studies of magnetoresistance for Si whiskers with boron concentration in the vicinity of MIT at cryogenic temperatures have shown that:

– for unstrained crystals the decrease of doping level leads to magnetoresistance increase at high magnetic fields up to 14 T;

– uniaxial compressive strain ($\varepsilon = -3.8 \cdot 10^{-3}$ r.u.) at 4.2 K of silicon whiskers with $\rho_{300\ K}$ = 0.011 Ohm·cm (in the vicinity of MIT from the metallic side) leads to the significant increase of magnetoresistance at high magnetic fields (Fig. 1a) if compared to the magnetoresistance of unstrained crystals;

– oppositely, compressive strain leads to significant decrease of magnetoresistivity for Si crystals with $\rho_{300\ K}$ = 0.013 Ohm·cm (in the vicinity of MIT from the insulating side) (Fig. 1b), that corresponds to the results of [10] for high resistivity silicon.

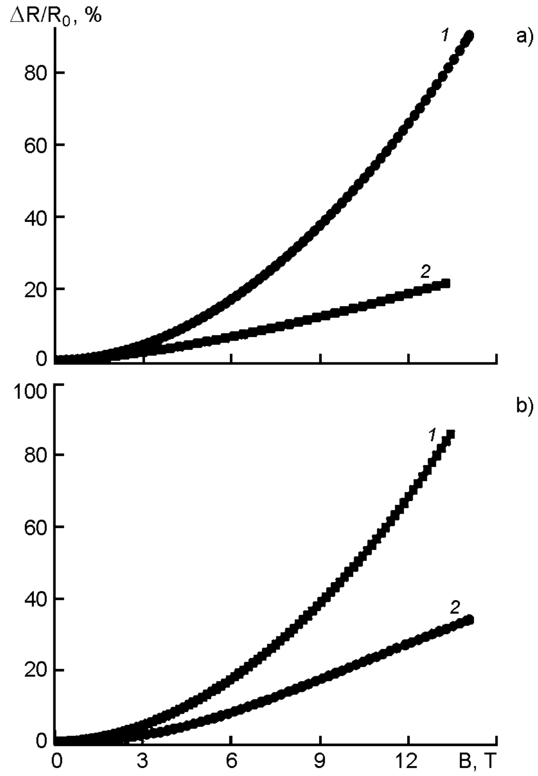

Fig. 1. Magnetoresistance at $T = 4.2$ K of p-type Si whiskers with ρ_{300K} = 0.011 Ohm·cm (a); ρ_{300K} = 0.013 Ohm·cm (b): *1* — unstrained crystal; *2* — under uniaxial compressive strain $\varepsilon = -3.8 \cdot 10^{-3}$ r. u.

Due to the weak localization of carriers the resistance of Si whiskers with metallic type of conductivity ($\rho_{300\ K}$ = 0.006 Ohm·cm) slightly depends on the magnetic field in the whole studied range up to 14 T. The change of magnetoresistance magnitude at 4.2 K is no more than 1 % at magnetic field 4 T for both unstrained and uniaxial compressive strained crystals. The studies of strain effect on the magnetoresistance for heavily boron doped Si whiskers at low temperatures shown the possibility to create mechanical sensors based on such whiskers operating at high magnetic fields and low temperatures.

Few studies of strain induced effects in electron irradiated silicon were carried out with the aim to explain the nature of radiation defects, but the influence of irradiation on silicon piezoresistance was not estimated [8, 11]. Our studies of strain induced effects in boron doped silicon whiskers under electron irradiation with energy 10 MeV and fluence $\Phi = 1 \cdot 10^{17} - 5 \cdot 10^{17}$ el/cm^2 at room temperature were carried out. It was established before that the electron irradiation with the energy of 10 MeV leads to increase of resistivity of boron doped silicon whiskers with $\rho_{300\ K} = 0.006 - 0.013$ Ohm·cm in the temperature range of 4.2 – 300 K [4]. It is worthy to emphasize that high-energy electron irradiation with fluence of $\Phi = 1{\cdot}10^{17}$ el/cm^2 at room temperature did not lead to substantial changes (within 1 – 2 %) of crystal resistivity, while the fluence increase up to $\Phi = 1{\cdot}10^{18}$ el/cm^2 resulted in the increase of resistivity, especially in the low temperature range [4].

The influence of electron irradiation on the gauge factor of silicon whiskers in the temperature range 4.2 – 300 K has been studied. After high energy electron irradiation *p*-type Si whiskers were subjected to uniaxial strain according to the method described in [3]. The temperature dependences of resistivity for unstrained and strained Si whiskers before and after irradiation were measured. Fig. 2 represents the temperature dependences of the gauge factor for heavily boron doped Si whiskers and with boron concentration in the vicinity of MIT before and after irradiation, calculated from the obtained experimental data.

The following peculiarities of gauge factor behaviour at low temperatures have been revealed:

— in heavily doped Si whiskers with $\rho_{300\ K} = 0.006$ Ohm·cm, in which the classical piezoresistance has been observed, the electron irradiation with energy of 10 MeV and fluence of $\Phi = 5{\cdot}10^{17}$ el/cm^2 don't leads to the change of gauge factor at liquid helium temperature (Fig. 2a), that gave the possibility to create on their basis piesoresistive sensors stable to electron irradiation

— in Si whiskers with boron concentration in the vicinity of MIT and resistivity $\rho_{300K} = 0.0114$ Ohm·cm the electron irradiation ($E = 10$ MeV, $\Phi = 5{\cdot}10^{17}$ el/cm^2) caused a significant decrease of gauge factor *GF* at 4.2 K, but in the irradiated crystals quite high values of gauge factor are preserved, proper for non-classical piezoresistance (Fig. 2b).

The complex studies aimed to create piezoresistive pressure sensors based on doped silicon whiskers operating at low temperatures were carried out. Heavily doped Si whiskers with $\rho_{300K} = 0.006$ Ohm·cm with metallic-type conductivity could be applied in mechanical sensors operating in wide temperature range 4.2 – 300 K. Silicon whiskers ($\rho_{300K} = 0.014$ Ohm·cm) with the giant gauge factor at low temperatures could be applied to create high-sensitive mechanical sensors operating at cryogenic temperatures.

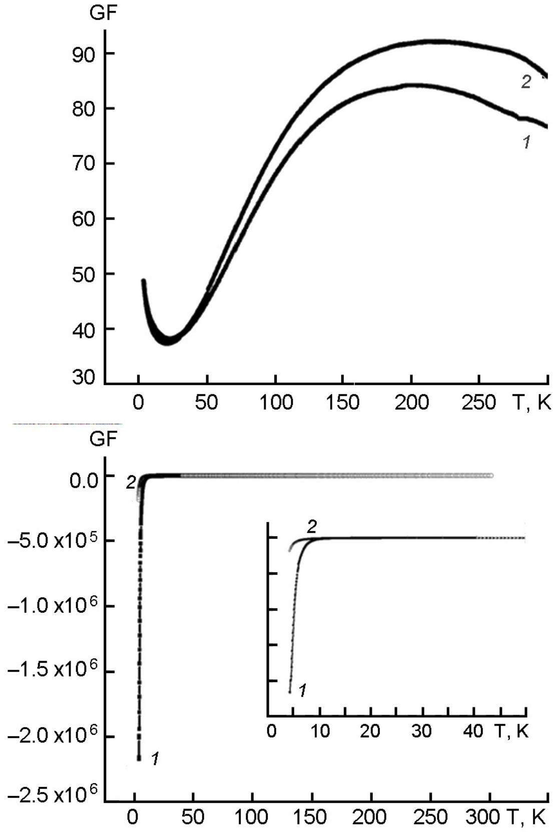

Fig. 2. Temperature dependences of gauge factor for *p*-type Si whiskers with $\rho_{300K} = 0.006$ Ohm·cm (a); $\rho_{300K} = 0.0114$ Ohm·cm (b): non-irradiated (*1*) and after electron irradiation with $E = 10$ MeV and $\Phi = 5{\cdot}10^{17}$ el/cm^2 (*2*).

Low temperature piezoresistive pressure sensors have been developed:

— based on heavily boron doped Si whiskers ($\rho_{300K} = 0.006$ Ohm·cm) operating in the temperature range 4.2 – 300 K;

— based on Si whiskers with boron concentration in the vicinity of MIT ($\rho_{300K} = 0.014$ Ohm·cm) operating at temperature 4.2 K.

The graduating characteristics of these pressure sensors at 4.2 K as dependences of output signal vs pressure are presented in the Table. It is evident from the Table that the pressure sensor based on Si whisker with resistivity $\rho_{300K} = 0.014$ Ohm·cm have significantly higher output at 4.2 K in comparison with the sensor based on heavily boron doped Si whiskers with $\rho_{300K} = 0.006$ Ohm·cm.

4. Conclusions

The complex studies of strain induced effects in boron doped silicon whiskers at low temperatures at high magnetic fields up to 14 T and under electron irradiation were carried out.

The effect of uniaxial strain on magnetoresistance of Si whiskers with different boron doping at temperature 4.2 K was studied. The character of magnetoresistance' change for Si whiskers with boron concentration in the vicinity of MIT at 4.2 K under uniaxial compressive strain was revealed. It was shown that heavily doped Si whiskers with metallic conductivity (ρ_{300K} = 0.006 Ohm·cm) are characterized by small magnetoresistance at high magnetic fields up to 14 T, which remains the same under uniaxial compressive strain. That opens the possibility to create on their basis piezoresistive sensors operating at high magnetic fields and cryogenic temperatures.

The influence of electron irradiation on gauge factor of boron doped silicon whiskers in the temperature range 4.2 – 300 K has been studied. It was shown that heavily doped *p*-type Si whiskers don't change their gauge factor at low temperatures after electron irradiation with energy 10 MeV and fluence $\Phi \le 5\cdot10^{17}$ el/cm^2, while the gauge factor of Si whiskers with boron concentration in the vicinity of MIT after such irradiation is decreased. The high-sensitive sensors to measure liquid helium pressure on the basis of *p*-Si whiskers with boron concentration in the vicinity of MIT with non-classic piezoresistance at cryogenic temperature and pressure sensors based on heavily doped Si whiskers for the temperature range 4.2 – 300 K were developed. It was shown that boron doped silicon whiskers are excellent materials for low temperature piezoresistive mechanical sensors operating in harsh conditions: high magnetic fields and electron irradiation.

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Деформаційно стимульовані ефекти у ниткоподібних кристалах кремнію *p*-типу за низьких температур

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Проведено комплексні дослідження деформаційно-стимульованих ефектів у ниткоподібних кристалах (НК) кремнію *p*-типу, легованих бором, з кристалографічною орієнтацією <111> в інтервалі температур 4,2 – 300 К і магнітних полях до 14 Тл, опромінених електронами високих енергій. Виявлено особливості п'єзомагнетоопору у сильнолегованих бором НК Si та з концентрацією бору поблизу переходу метал-діелектрик за низьких температур. Вивчено також вплив електронного опромінення з енергією 10 МеВ і флюенсом $\Phi = 5\cdot10^{17}$ ел/см^2 на коефіцієнт тензочутливості НК Si, легованих бором, за низьких температур. Розроблено високочутливий п'єзорезистивний сенсор тиску рідкого гелію на основі НК кремнію з гігантським коефіцієнтом тензочутливості. Сильнолеговані НК кремнію з класичним п'єзоопором успішно використовуються у сенсорах механічних величин для широкого інтервалу температур 4,2 – 300 К.