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Polysilicon on Insulator Structures for Sensor Application at Harsh Conditions

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The paper deals with an investigation of conductance of recrystallized p-type polysilicon-on-insulator layers irradiated with electrons of high energies in temperature range 4,2 - 300 K and high magnetic fields (up to 14 T). The aim of paper is to obtain material with properties appropriated for design of sensors operating in harsh employment conditions.

Key words: polysilicon-on-insulator, sensor, magnetoresistance, SOI-structures

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Introduction

Polycrystalline silicon layers on the surface of oxidized silicon plate, i.e. SOI-structures, are widely used in modern microelectronics. Generally chemical deposition from vapor phase is used to form such layers. In contrast to monocrystalline silicon in polycrystalline layers the low mobility of electrons and holes, as well as the short lifetime of charge carriers, is observed due to a big amount of structure defects, which are known to be scattering and recombination centers [1, 2]. Structure defects decreasing by laser recrystalization of initial poly-Si makes it possible to substantially increase the mobility of charge carriers in a layer. This gives prospects to create a high performance and highly integrated microelectronic devices and physical sensors on their basis, and to create microchips with three-dimensional elements integration for signal processing in smart sensors [2, 3].

The microelectronic sensors of mechanical and thermal values for environmental and elevated temperatures are known to be created on the basis of poly-Si [3, 4]. Our previous researches [5 - 8] have shown the possibility of creation of mechanical and thermal sensors on the basis of laser recrystallized poly-Si layers on insulator, operable in a wide temperature range (4,2 – 300 K). A set of low temperature investigations of doped polysilicon layers properties has to be conducted in order to estimate the irradiation stability of such sensors on the basis of SOI-structures, irradiated with high energy electrons, and to estimate the magnetic field effect on these characteristics.

The aim of this paper is to estimate the possibility of SOI-structures application in sensors of physical values operating at harsh conditions – at cryogenic temperatures, high magnetic fields and at the influence of electron irradiation.

I. Experimental procedure and objects of research

Specially designed test structures were used for electric properties measurement of polysilicon layers. The dimensions of polysilicon resistor in SOI-structure were 80 μm × 8 μm × 0,5 μm. Two groups of samples have been investigated – with initial boron concentration of $2{,}4 \times 10^{18}$cm^{-3} and $3{,}9 \times 10^{19}$cm^{-3} respectively. Improvement (stabilization) of technical performances of SOI-structure is approached due to laser recrystallization of their layers. After the laser recrystalization the charge carriers concentration evaluated from the Hall coefficient studies consisted of $4{,}8 \times 10^{18}$cm^{-3} for the first group of polysilicon samples and $1{,}7 \times 10^{20}$cm^{-3} for the second one.

An ion beam implantation method has been used for doping of polysilicon. The polysilicon layers have been recrystalized by laser beam scanning (wavelength l = 1,06 μm) of the surface of silicon plates oriented along the (100) direction, which were previously thermally oxidized to thickness of 1 μm. The poly-Si layers 0,5 μm thick have been deposited from a vapor phase in a low pressure reactor at 625 °C. In order to provide a specified thermal profile in an area of radiation thermal influence a SiO_2 and Si_3N_4 coating have been used. By controlling the efficiency of absorption of irradiated structure using antireflecting surfaces the temperature profile of process can be controlled (Fig. 2).

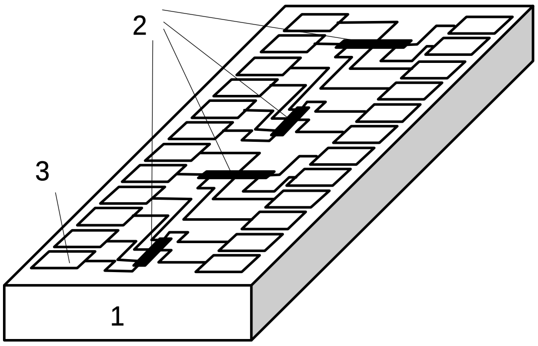


Fig. 1. Schematic illustration of experimental sample on the basis of SOI-structure: 1 – monosilicon substrate, 2 – polysilicon resistor, 3 – contact plates.

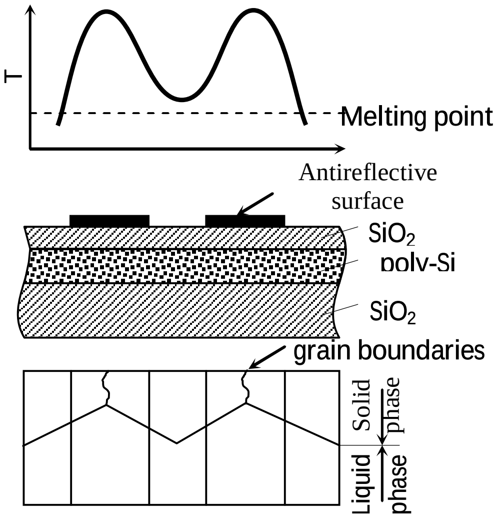


Fig.2. The modulation of a temperature profile in melt area during the recrystalization of polysilicon layer on insulator substrates [9].

Besides antireflecting covering prevents the diffluence of the molten material which can negatively influence on the film orientation. At optimum conditions of laser recrystalization the polysilicon layers with grain sizes of up to 20 × 500 μm have been obtained [9].

The low temperature studies of SOI-structures have been carried out in a temperature range of 4,2 - 300K at magnetic fields up to 14T. The measurements of the samples resistance at cryogenic temperatures have been held in International Laboratory of Strong Magnetic Fields and Low Temperatures (Wroclaw, Poland). The samples have been cooled down to 4,2 K in the helium cryostat (ГКОП). A special inset with the bifilar winding heater has been used for the heating-up of samples to room temperature. The stabilized electrical current of 1 – 100 μA depending on the resistance of the sample being investigated has been generated by Keithley 224 current source. The Keithley 2000 and Keithley 2010 digital voltmeters with the simultaneous automatic indications registration via the parallel port of PC, the vizualization and saving the data arrays into files have been used to measure the voltage at the potential contacts of samples, the output of thermocouple and of the sensor of magnetic field with the accuracy of upto 1×10^{-6} V.

The Bitter-magnet based setup has been used for investigations of the strong magnetic fields effect on the samples. The induction of a magnet was 14 T, deflection time was 1,75 T/min and 3,5 T/min for 4,2 K and higher temperature range respectively. The investigated samples have been irradiated in the electron accelerator Microtron M-30 in the Institute of electron physics of National Academy of Sciences of Ukraine (Uzhgorod). The irradiation with high energy electrons of 10 MeV and fluence of $\Phi = 1 \times 10^{16}$ el/cm^2 and 1×10^{17} el/cm^2 has been conducted using the standard technique.

II. Results and discussion

Similarly to our previous investigations a typical features of polysilicon have been observed and the possibility of SOI-structures application in microelectronic sensors has been shown [6, 10]. For unrecrystalized poly-Si layers with charge carriers concentration of $2{,}4 \times 10^{18}$cm^{-3} the phenomena of negative magnetoresistance has been observed (Fig. 3). Together with the results of resistivity investigations this evidences the hopping conductivity of polysilicon at low temperatures. Indeed the conductivity of such samples in low temperature range changes in accordance to Mott law ($\ln\rho \sim T^{-1/4}$) as it is obvious from Fig. 4.

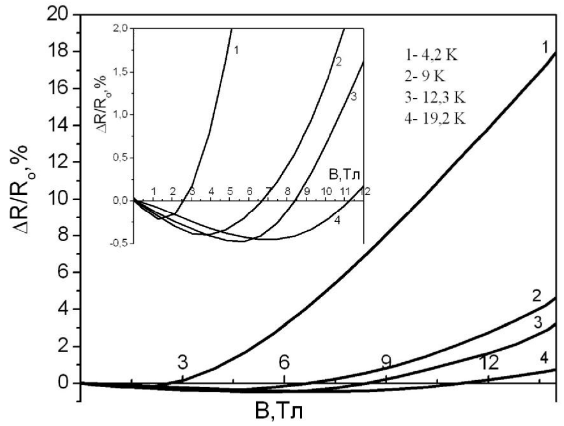


Fig. 3. Longitudinal magnetoresitance of unrecrystallized poly-Si layers with p_{300K}= $2{,}4 \times 10^{18}$ cm^{-3} at various temperatures: 1 – 4,2 K, 2 – 9 K, 3 – 10,3 K, 4 – 19,2 K. Inset: temperature dependence of magnetoresistance.

In general the electrical conductivity of polycrystalline material is similar to the conductivity of disordered semiconductors and in a case of liquid helium temperatures it can be described by a percolation theory [11]. Let us discuss how magnetic field affects the conductivity of disordered systems. This influence is different depending on conductivity type.

According to [11, 12] the conductivity of polycrystal material is very similar to the conductivity of disordered semiconductors. Depending on the average grain size, the doping level and some other factors different mechanisms of charge carriers transfer become dominant

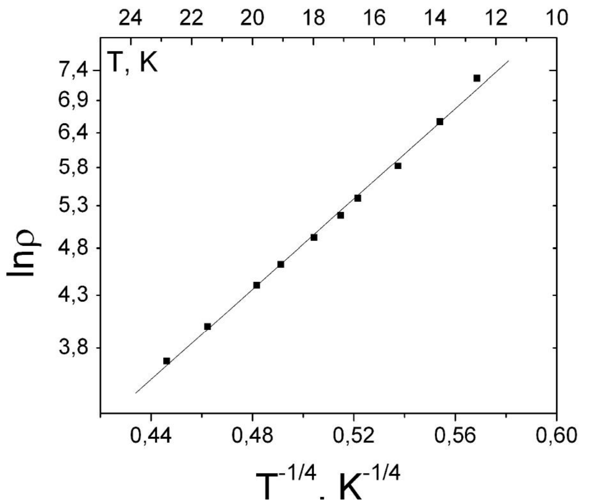


Fig. 4. Resistivity versus temperature for unrecrystallized poly-Si with charge carrier concentration p_{300K} =2,4×10^{18} cm^{-3} .

(from over-barrier mechanism to percolation of electrons via the states of grain boundaries traps).

If the grain is fully or almost fully depleted with charge carriers the electrical conductivity is realized by the charge carriers transfer over the localized states at grain boundaries. This conductivity can be observed only for low doping levels and small grain sizes independently on the temperature.

At cryogenic temperatures, at which a substantional freezing-out of charge carriers is expected, the amount of carriers in the grain volume becomes very small, except the case of very high doping level corresponding to metallic type of electrical conductivity. Thus the quantum mechanism of charge carriers transfer via the grain boundaries states should be dominant. The difference in barriers height at grain boundaries results in the random potential profile, caused by the distortion of bands. That is why such a system should be considered as a very heavily doped and compensated semiconductor in which grain boundaries states play the role of counterdopant. As the temperature decreases the contribution of quantum mechanism of transfer increases and it can be described with the theory of charge carriers percolation [12, 13].

In order to confirm the Mott law the measurements of megnetoresistance in the range of hopping conductivity have been conducted.

As for now, there are experimental results that have proven the satisfaction of the Mott law in heavily doped semiconductors. It has been shown [14] that the increase of compensation level in n - Ge causes the magnetoresistance does not saturate in strong magnetic fields. In that paper the observation of negative magnetoresistance, which in sufficiently strong magnetic fields converts into positive, has been pointed out. The lowest the temperature is the lower is the induction of magnetic field (B) at which positive magnetoresistance occurs.

It has been shown in [15] that the following expression is valid for two different temperatures:

$$\frac{H_0^1}{H_0^2} = \left(\frac{T_1}{T_2}\right)^{1/2} \qquad (1)$$

where H_0 is magnetic field, at which magnetoresistance is equal to zero. According to theoretical assumptions presented in [15] this magnetic field is proportional to the temperature of observation ($H_0 \sim T^{3/8}$), what has been evidenced during the experimental investigations (Fig. 5). This fact confirms the Mott hopping conductivity at $B = 0$.

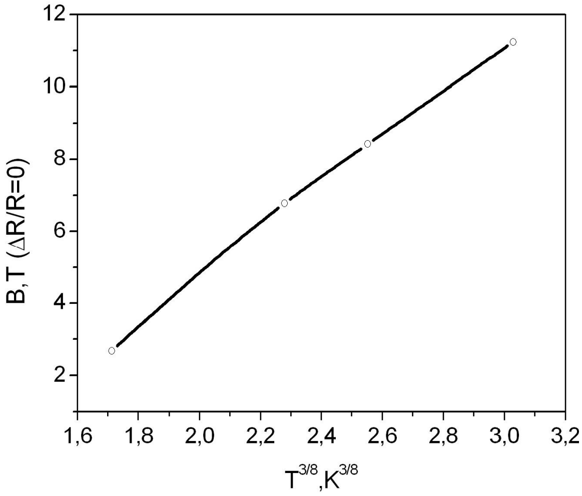


Fig. 5. Temperature dependency of magnetic field induction for unrecrystalized polysilicon layers with charge carriers concentration of p_{300K} = 2,4 × 10^{18} cm^{-3}.

Studies of [16] show that the model of charge carriers capturing by traps on grain boundaries, introduced by Seto [17], is the most proper for accounting of grain boundaries influence on electronic properties of polycrystalline material. This model suggest that due to defective structure the charge carriers traps appear in grain boundaries. This structure consists of disordered atoms of the main material, that are dangling bonded to surroundings. Energetic states of traps capture the part of charge carriers from ionized impurities, distributed in grain boundaries surroundings. Due to this process the average amount of free charge carriers in polycrystalline material decreases and the potential barrier in space-charge region arises. Due to this barrier a free motion of charge carriers between separate grains is sufficiently reduced. That is why the laser recrystallization of fine-grained polysilicon is used in order to increase the average grain size and simultaneously reduce the total area of grain boundaries, at which a capturing of free charge carriers occurs. Besides, due to increased grain size and reduced grain boundaries contribution the laser recrystallization leads to the reduced poly-Si resistivity if compared to the initial unrecrystallized polysilicon. Thus, recrystallized polysilicon layers can be recommended for creation of microelectronic sensors on the basis of SOI-structures.

For example, it has been shown in [10], that heavily doped recrystallized polysilicon layers (p_{300K} = 1,7 × 10^{20} см$^{-3}$) are the most stable in magnetic field at 4,2 K. Such polysilicon layers can be recommended for creation of piezoresistive mechanical sensors, operable at cryogenic temperatures and at the influence of strong magnetic fields. At the same time the laser recrystallized polysilicon layers with carriers concentration of $p_{300K} = 4{,}8 \times 10^{18}$ $см^{-3}$are better candidates for more accurate mechanical sensors for cryogenic temperatures below 4,2 К [6].

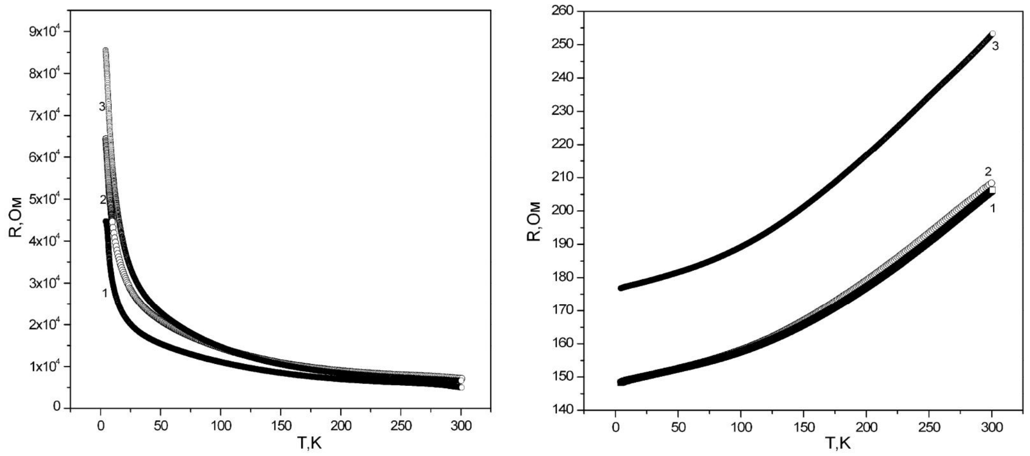
Taking into account a harsh conditions of SOI-based sensor application, recrystallized poly-Si layers with concentrations $p_{300K} = 4{,}8{\times}10^{18}$ cm^{-3} and $p_{300K} = 1{,}7 \times 10^{20}$ cm^{-3} have been irradiated by electrons with energy of 10 MeV and fluence $\Phi = 1 \times 10^{16} \div 1 \times 10^{17}$ el/cm^2 using a Microtron M-30 accelerator.

The studies of samples' conduction before and after the irradiation have been carried out in the temperature range of 4,2 K to 300 K. The temperature dependencies of resistance for laser recrystalized polysilicon layers with carrier concentration $4{,}8 \times 10^{18}$ cm^{-3} and $1{,}7 \times 10^{20}$ cm^{-3} before and after the electron irradiation are shown at Fig. 6.

As it is obvious from Fig.6, the resistance of poly-Si layers increases after the irradiation with high energy electrons. The most clearly this tendence reveals in samples with carrier concentration of $4{,}8 \times 10^{18} cm^{-3}$ (Fig. 6,a), while in heavily doped samples (Fig. 6,b) this dependency is less clear, as it is illustrated in table.

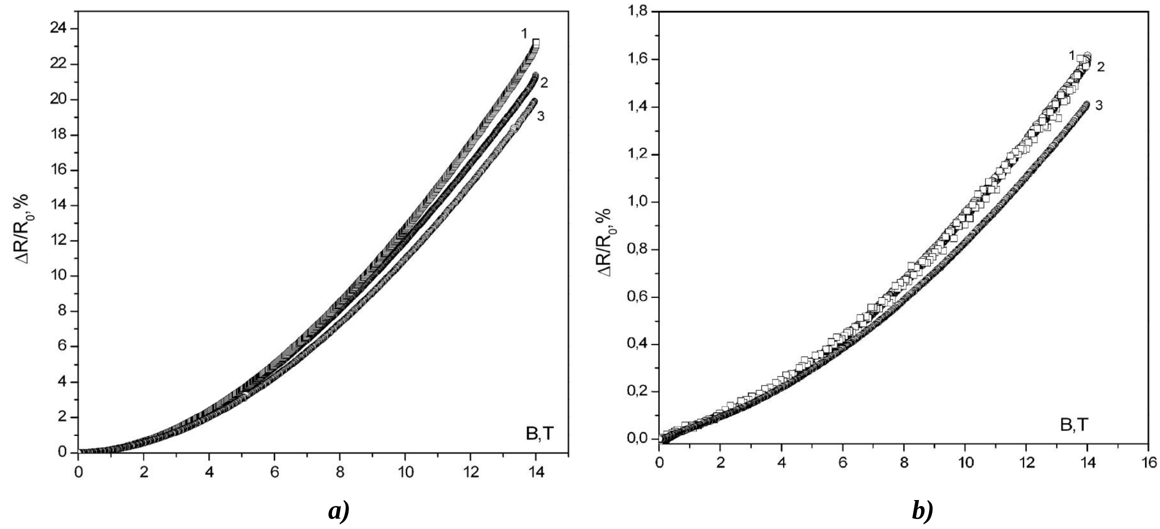
The electron irradiation influence on lateral magnetoresistance of polysilicon samples has been also studied in strong magnetic fields up to 14T at the temperature of liquid helium. The results of magnetoresistance measurements are depicted on Fig. 7.

As it is seen on Figures 6 and 7, the corellation is observed between the electron irradiation influence on conductivity and on the magnetoresistance of polysilicon layers at low temperatures. Due to the irradiation with high energy electrons the carrier mobility decrease in irradiated samples leads to the decrease of conductivity (Fig. 6) and of the magnetoresistance (Fig. 7) of polysilicon layers respectively, if compared to non-



a) *b)*

Fig. 6. Temperature dependencies of resistance of poly-Si layers with $p_{300K} = 4{,}8 \times 10^{18} cm^{-3}$ (a) and $1{,}7 \times 10^{20}$ cm^{-3} (б) before (1) and after high energy electron irradiation with fluence of $\Phi = 10^{16}$ el/cm^2 (2) and $\Phi = 10^{17} el/cm^2$ (3).



a) *b)*

Fig. 7. Transversal magnetoresitance of recrystallized poly-Si layers with $p_{300K} = 4{,}8 \times 10^{18} cm^{-3}$ (a) i $1{,}7 \times 10^{20} cm^{-3}$(b) before (1) and after high energy electron irradiation with fluence of $\Phi = 10^{16}$ el/cm^2 (2) and $\Phi = 10^{17} el/cm^2$ (3).

Table 1

Experimental results for samples, irradiated with high energy electrons

poly-Si T, K	$(R_{irr.}- R_{nonirr.})/R_{nonirr}\times10^2$, %			
	$\Phi = 1 \times 10^{16}$ el/cm^2		$\Phi = 1 \times 10^{17}$ el/cm^2	
	$P_{300K} = 4{,}8\times10^{18}$cm^{-3}	$p_{300K} = 1{,}7\times10^{20}$cm^{-3}	$p_{300K} = 4{,}8\times10^{18}$cm^{-3}	$p_{300K} = 1{,}7\times10^{20}$cm^{-3}
4,2	18	0,1	91	19
77	34	0,4	39	20
300	28	0,9	32	22

irradiated.

As it is known, the magnetoresistance for such material is expressed by the following equation [18]:

$$\frac{\Delta R}{R} = a\left(m B\right)^2 \qquad (2)$$

where *a*- stands for a coefficient accounting the charge carriers scattering, *m* is mobility and B designates the induction of magnetic field.

Taking into account the equation (2), one can conclude that the magnetoresistance decrease in experimental results for charge carriers concentration of $4{,}8\times10^{18}$ cm^{-3} and $1{,}7\times10^{20}$ cm^{-3} is caused by the decreasion of charge carriers' mobility in polysilicon layers.

The results of investigations have shown that heavily doped laser recrystallized poly-Si layers with charge carrier concentration $1{,}7\times10^{20}$cm^{-3} demonstrate a high radiation stability up to electron irradiations with energy 10 MeV and fluence $\Phi = 1 \times 10^{16}$ el/cm^2. Thus, they can be used for creation of radiation-resistant microelectronic sensors.

Conclusions

В результаті проведення експериментальних досліджень вивчено характер хімічного розчинення монокристалів CdTe і твердих розчинів $Cd_{0,96}Zn_{0,04}Te$ та $Cd_{0,8}Zn_{0,2}Te$ в травильних сумішах системи H_2O_2-HBr, досліджено кінетику процесу розчинення, побудовано графіки залежності швидкості розчинення вказаних напівпровідникових матеріалів від концентрації травника, швидкості обертання диску і температури та визначено механізм розчинення. Встановлено концентраційні межі розчинів, які можна використовувати для ХДП CdTe, $Cd_{0,96}Zn_{0,04}Te$ та $Cd_{0,8}Zn_{0,2}Te$. Показано взаємозв'язок уявної енергії активації із швидкістю обертання диску при розчиненні вказаних напівпровідників в бромвиділяючих травильних композиціях на основі гідроген пероксиду.

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Полікремній на ізоляторі для застосування в сенсорах, працездатних в складних умовах експлуатації

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В роботі досліджено електропровідність рекристалізованих шарів полікремнію на ізоляторі p-типу провідності, опромінених електронами високих енергій в температурному діапазоні 4,2 ÷ 300 К і в сильних магнітних полях до 14 Тл з метою прогнозування властивостей матеріалу для створення сенсорів фізичних величин, працездатних в жорстких умовах експлуатації.

Ключові слова: полікремній на ізоляторі, сенсор, магнітоопір, КНІ-структури.