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Charge Carrier Transport of Polysilicon in SOI-Structures at Low Temperatures

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The studies of temperature dependence of conductivity and magnetoresistance of SOI-structures with polysilicon resistors with carrier concentration $2{,}4\cdot10^{18}$ cm^{-3} before recrystallization in temperature range 4,2 – 300 K are presented. The dimensions of polysilicon resistor in SOI-structure are 80 μm × 8 μm × 0,5 μm.

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Introduction

The studies of conductivity of polysilicon on insulator (SOI) layers at cryogenic temperatures in high magnetic fields allow to obtain information about the carrier transport mechanism in polysilicon at low temperatures [1, 2], when significant freezing of carriers is expected. It is interesting to study, for example, the effect of strain on the conductivity of polysilicon layers at cryogenic temperatures to predict the possibility of application of such structures in mechanical sensors operating in harsh conditions (cryogenic temperatures, high magnetic fields). The microelectronic mechanical, thermal and medical sensors for environmental and elevated temperatures are known to be created on the basis of poly-Si [3 - 5]. Our previous investigations [6] have shown the possibility to create mechanical and thermal sensors on the basis of laser recrystallized poly-Si layers on insulator, operable in the wide temperature range (77 – 300 K). However, peculiarities of low-dimensional polysilicon in SOI structures allow us to predict the properties of material for creation of sensors operating at low temperature range.

In our previous work [7, 8] the results of studies the temperature dependencies of resistance for such poly-Si layers in the temperature range 4.2 - 300 K were presented. On the other hand, more comprehensive studies of nonrecrystallized polysilicon layers in SOI structures at low temperatures allow to consider physical aspects of charge carrier transport, which will enable to predict properties of the material depending on its structure. The aim of this work was to study the properties of polysilicon in SOI structures to determine the effect of material dispersion on low-temperature conductivity, the results of which open an opportunity to create a high performance and highly integrated microelectronic devices and physical sensors on their basis.

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 consist of 80 μm × 8 μm × 0,5 μm. Two groups of samples were under investigation – with initial boron concentration of $2{,}4\times10^{18}$ cm^{-3} and $3{,}9\times10^{19}$ cm^{-3}, correspondingly. Improvement (stabilization) of technical performances of SOI-structure is approached due to laser recrystallization of their layers. As it was shown from Hall coefficient measurement, a charge carrier concentration in the investigated samples consists of $4{,}8\times10^{18}$ cm^{-3} and $1{,}7\times10^{20}$ cm^{-3} correspondingly. Low temperature investigations of SOI-structure were conducted in temperature range 4,2 – 300 K at magnetic field up to 14 T. The samples have been cooled down to 4,2 K in the helium cryostat. A special inset with the bifilar winding heater has been used to heat-up samples to the room temperature. The stabilized electrical current of 1–100 μA depending on the resistance of the sample being studied has been generated by Keithley 224 current source. The Keithley 2000 and Keithley 2010 digital voltmeters with the simultaneous automatic 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 magnetic field sensor with the accuracy of up to 1×10^{-6} V. The Bitter-magnet based

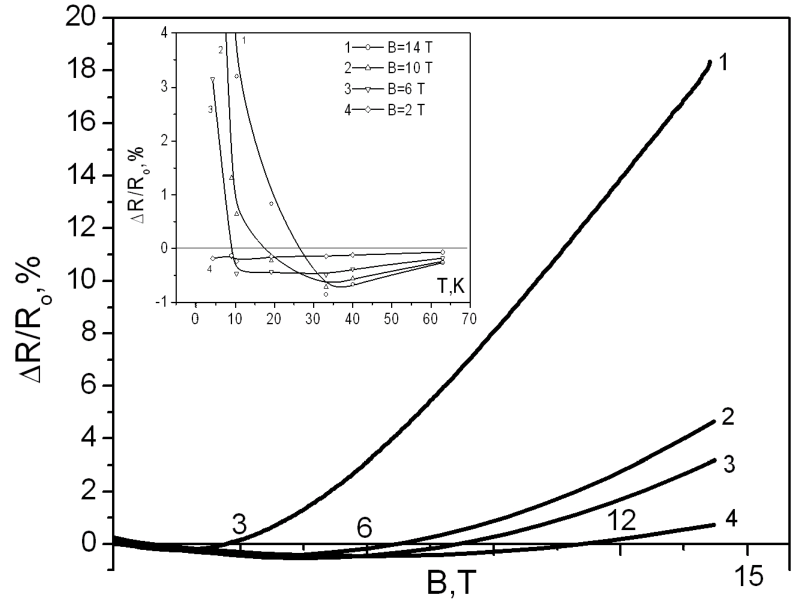

Fig. 1. Magnetoresitance of unrecrystallized poly-Si layers with p_{300K} = 2,4×10^{18}cm^{-3} at various temperatures: 1 – 4,2 K; 2 – 9 K; 3 – 10,3 K; 4 – 19,2 K. Inset: temperature dependence of magnetoresistance

setup has been used to study the effect of strong magnetic fields on the samples. The induction of the magnet was 14 T, deflection time 1,75 T/min and 3,5 T/min at 4,2 K and higher temperature range respectively.

II. Experimental results dc measurement

As a result of typical DC investigations at temperatures range 4,2 – 300 K and high magnetic fields up to 14 T the following property peculiarities of polysilicon in SOI-structures have been obtained. So, for unrecrystalized poly-Si layers with charge carriers concentration of 2,4 · 10^{18}cm^{-3} the phenomena of negative magnetoresistance has been observed (Fig. 1). At the same time nonrecrystallized polysilicon layers with carrier concentration of 2,4 · 10^{18} cm^{-3} have significant temperature dependence what indicates the presence of a large number of grain boundaries (Fig. 2.)

These results evidence hopping conductivity of polysilicon at low temperatures. As it seen from fig. 3 the conductivity of these samples in the low temperature range varies by the Mott law (lnρ ~ T$^{-1/4}$) (Fig. 3).

In general the electrical conductivity of polycrystalline material is similar to the conductivity of disordered semiconductors and in the case of liquid helium temperatures it can be described by the percolation theory [9, 10]. Let us discuss how magnetic field affects the conductivity of disordered systems. This influence is different depending on the conductivity type. Depending on the average grain size, the doping level and some other factors, different mechanisms of charge carriers transport become dominant (from over-barrier mechanism to percolation of electrons via the states of

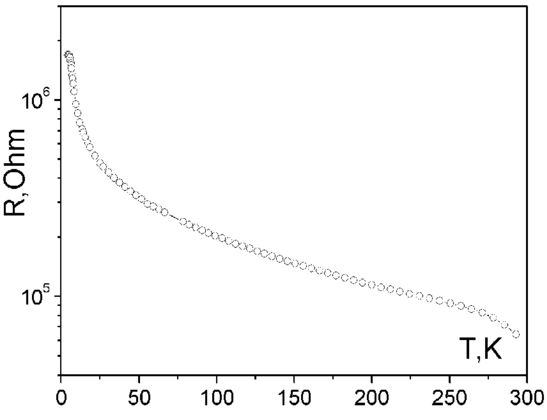

Fig. 2. Temperature dependence of resistance for unrecrystallized poly-Si layers with carrier concentration p_{300K} = 2,4×10^{18} cm^{-3}.

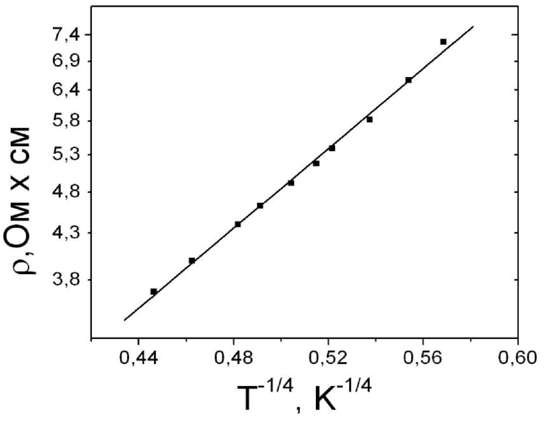

Fig. 3. Resistivity versus temperature for unrecrystallized poly-Si with charge carrier concentration p_{300K} = 2,4·10^{18} cm^{-3}.

grain boundaries traps). If the grain is fully or almost fully depleted with charge carriers the electrical conductivity is realized by the charge carriers transport 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 transport 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 by the theory of charge carrier percolation [10, 11].

As for now, there are experimental results that proved the satisfaction of the Mott law in heavily doped semiconductors. It has been shown [12] that the increase of compensation level in n-Ge causes that 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 [13] that the following expression is valid for two different temperatures: $H_o^1/H_o^2 = (T_1/T_2)^{1/2}$, where H_0 is the magnetic field, at which magnetoresistance is equal to zero. According to theoretical assumptions presented in [13], this magnetic field is proportional to the temperature of observation ($H_0 \sim T^{3/8}$), that has been evidenced during the experimental studies (Fig. 4). This fact confirms the Mott hopping conductivity at B = 0.

Besides the exponentially high values of positive magnetoresistance (Fig. 1) indicates a hopping conduction the positive component of which is related to the compression of localized state wave function at magnetic field. The model that predicts the hopping probability determined by the degree of spin polarization at magnetic field has been proposed.

It was shown in [9, 14] that for correct description of positive part of magnetoresistance besides of effect of compression of wavelength function it is necessary to accounting spin-dependent transport. At such conditions effective Miller-Abrahams net is formed as by once (D°) and by twice (D^-) occupied states. Twice occupied states have two electrons with opposite spins, which leads to additional contribution in the sample magnetoresistance. To describe the contribution one can propose two models. According to first one Zeeman splitting of energetic bands takes place in the vicinity to Fermi level where hopping conductance appears [15]. However, this approach leads to uncorrected field and temperature dependencies of magnetoresistance in weak magnetic fields. The second model implies that the probability of jumps involving D^- states is determined by the degree of spin polarization of the wave function in a magnetic field [16].

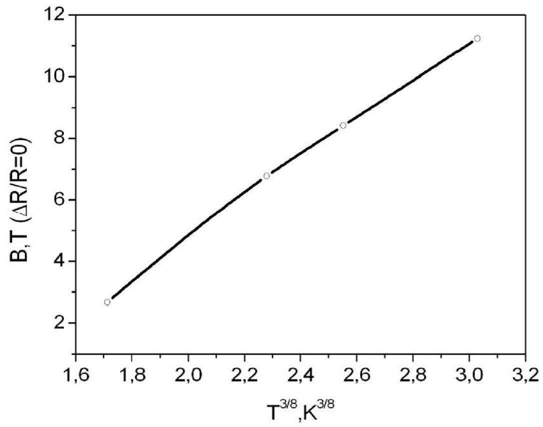

Fig. 4. Temperature dependence of magnetic field induction for unrecrystalized poly-Si layers with carriers concentration of $p_{300K} = 2{,}4\times10^{18}$cm^{-3}.

According to the model expression for parameter T0 in Mott law (at α = 1/4) has the following

$$T_0 = \frac{2h_c}{k_B(g_1 a_1^3 + g_2 a_2^3)} \tag{1}$$

and allows us to found quadratic on magnetic field induction magnetoresistance accounting simultaneous contribution of compression of wave function and spin-polarization effects.

$$\ln[r(H)/r(0)] = \left(\frac{T_0}{T}\right)^a a\, A_{eff}(T)\left(\frac{mH}{k_B T}\right)^2 \tag{2}$$

In equation (1), (2) parameter T0 is expressed due to renormalized densities of states $g_{1,2}$ and radius of localization $a_{1,2}$ for D^0 and D^- – states, μ is effective magnetic moment of electron and parameter A_{eff} has a form

$$A_{eff} = A + BT^{2-2a} \tag{3}$$

where $A = (g_2 a_2^3 - g_1 a_1^3)/(g_2 a_2^3 + g_1 a_1^3)$

$$B = \frac{20}{2016}\frac{a_2^4 e^2 k_B^2 T_0^2}{\mathbf{h}^2 m^2} \tag{4}$$

Taking into account experimental data of temperature dependency of magnetoresistance plotted in coordinates $T^{2-2\alpha}$ one can obtain $A_{eff}(T)$ value. Extrapolation the $A_{eff}(T)$ curve to T = 0 allows us to obtain parameter A; slope of curve $A_{eff} = f(T^{2-2\alpha})$ gives opportunity to determine parameter B as well as radius of localization and density of states on Fermi level for twice occupied states of centers.

Treatment of experimental data in Mathcad environment allows us to obtain the parameters for low dimensional polySi layers. The obtained value of A = 0,003 gives us a possibility to calculate radius of localization, density of states and average distance of jumps on localized states for poly-Si sample: α_1 = 6 Å, $g_1 = 1{,}3\cdot10^{21}$ eV·cm^{-3}, 31 < R < 36 for once occupied

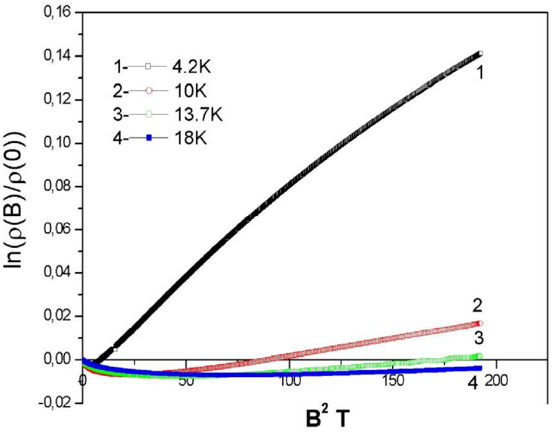

Fig. 5. Logarithmic dependence magneto-resistance of unrecrystallized poly-Si layers with $p_{300K} = 2{,}4\times10^{18}$ cm^{-3} at various temperatures: 1 – 4,2 K; 2 – 10 K; 3 – 13,7 K; 4 – 18 K.

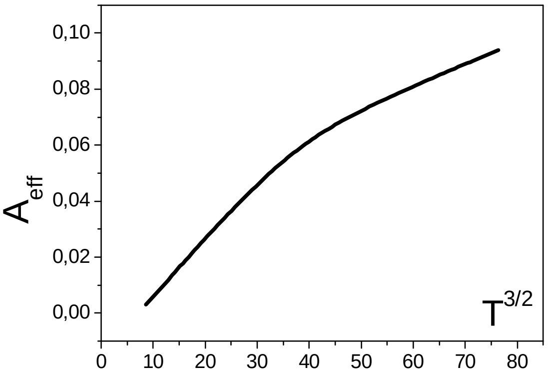

Fig. 6. Temperature dependence of the parameter A_{eff} magnetoresitance of unrecrystallized poly-Si layers with $p_{300K} = 2{,}4\times10^{18}$cm^{-3}.

centers and α_2= 23 Å, $g_2 = 2\cdot10^{19}$ eV·cm^{-3} 121 < R < 140 for twice occupied centers.

Average distance of jumps on localized states R is calculated according to equation:

$$R(T) = \frac{3}{8}a\left(\frac{T_0}{T}\right)^{1/4} \qquad (5)$$

It follows from equation (5) that at temperature decrease parameter R increases. As a result the probability of jumping spatially more distant but energetically closer to centers of localization increases, which is the reason for reducing the activation energy of hopping conductance.

Calculated radius of jumps suggest about the nature of the mechanism of hopping conduction in investigated samples. For polycrystalline materials, depending on the average grain size and doping level it becomes the dominant one or the other mechanism of transport of charge carriers (from barrier mechanism to the flow of electrons in trap states at the grain boundaries) [17].The barrier mechanism is hardly occured at low temperatures because of significant freezing carriers (small number of carriers in the grain bulk) and small values of thermal energy kT needed to jump through barrier. So, the main transport mechanism in the range of hopping conductance should be reffered to conductance on grain boundaries. We compare the average grain size of unrecrystallized polycrystalline silicon, whose value is about 30 nm, with average jump radii obtained from theoretical calculations based on experimental data values on hopping conductance in singly and doubly occupied states – 30 A and 130 A, respectively. Short jump radius of hopping conductance on single occupied states - in order magnitude smaller than grain diameter - indicates in significant seggregation of impurities on grain boundaries. Jumping on the double-occupied states are characterized by comparable magnitude range jump with grain size. The latter mechanism is interesting in terms of research using external magnetic fields. The presence of two electrons on the impurity of different (parallel or antiparallel) spin orientation can lead to the emergence of the phenomenon of anomalous magnetic field of negative or positive magnetoresistance. Our own experiments have shown that the samples at low temperatures observed negative magnetoresistance, which can be attributed to the conductivity in double occupied impurity states.

The experimental data shows that accounting D^- states no significant effect on the parameter T0 in Mott law leading to a small correction in the temperature dependence of the conductivity in zero magnetic fields, which nevertheless is essential in the quantitative description of the magnetoresistance.

Conclusions

The results of complex investigation of polysilicon in SOI structures with concentration p_{300K}= $2{,}4\times10^{18}$cm^{-3} allow us to determine influence of material microstructure on its magneto-transport properties at cryogenic temperatures. So, at temperature range 10÷25 K the thermal behavior of resistance of unrecrystallized poly-Si with carrier concentration $2{,}4\times10^{18}$ cm^{-3} approximately could be presented in terms of the Mott law ($\ln\rho \sim T^{-1/4}$), what indicates on hopping type of conduction in such samples at low temperatures. Treatment of experimental data allows us to obtain the parameters for low dimensional polySi layers with $p_{300K} = 2{,}4\times10^{18}$cm^{-3}, in particular, calculated radius of localization, density of states and average distance of jumps on localized states α_1 = 6 Å, $g_1 = 1.3\cdot10^{21}$ eV·cm^{-3}, 31 < R < 36 for once occupied centers and α_2 = 23 Å, $g_2 = 2\cdot10^{19}$ eV·cm^{-3} 121 < R < 140 for twice occupied centers in the hopping conduction region.

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