ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 12, № 3 (2011) С. 753-756

PHYSICS AND CHEMISTRY OF SOLID STATE
V. 12, № 3 (2011) P. 753-756

ISSN 1729-4428

A.A. Druzhinin[1,2], I.T. Kogut [3], Yu.M. Khoverko[1,2], R.M. Koretskii [1]

Influence of Dispersion of Polysilicon on Low-Temperature Conductivity in SOI Structures

[1]National Lviv Polytechnic University, Lviv, Ukraine
[2]International Laboratory of Low Temperatures and High Magnetic Fields, Wroclaw, Poland
[3]Precarpathian university named after V.Stephanyk, Iv-Frankivsk, Ukraine

The studies of temperature dependence of conductivity, impedance analysis and magnetoresistance of SOI-structures with polysilicon resistors with carrier concentration $3{,}9\cdot10^{19}$ cm^{-3}, $2{,}4\cdot10^{18}$ cm^{-3} before recrystallization and $1{,}7\cdot10^{20}$ cm^{-3}, $4{,}8\cdot10^{18}$ cm^{-3} after recrystallization in temperature range 77–300K are presented. The dimensions of polysilicon resistor in SOI-structure are 80 μm × 8 μm × 0,5 μm.

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

Стаття поступила до редакції 23.05.2011; прийнята до друку 15.06.2011.

Introduction

The studies of conductivity of polysilicon on insulator layers at cryogenic temperatures in high magnetic fields allow to obtain information about the carrier transport mechanism in polysilicon at low temperatures, when significant freezing of carriers is expected [1]. It is interesting to study 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). In our previous work [2] 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 investigation of recrystallized and nonrecrystallized polysilicon layers in SOI structures by impedance analysis method will enable to predict properties of the material depending on its structure [3]. The aim of this work was to study the properties of polysilicon in SOI structures by impedance analysis method to determine the effect of material dispersion on low-temperature conductivity.

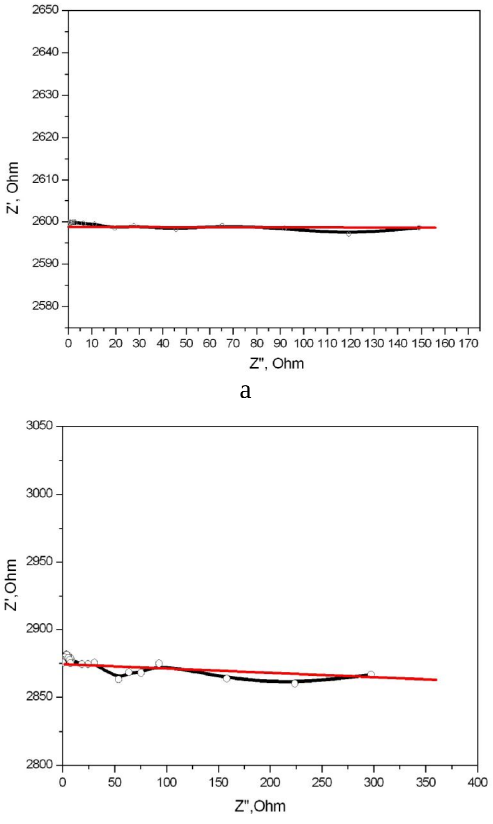
I. Experimental procedure and objects of research

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 4,2-300K at magnetic field up to 14T.

Essentially, the impedance analysis method is that the studied sample is excited by a small sinusoidal signal is measured while it caused alarm at the exit. These measurements were carried out in the frequency range 10^{-2}–10^{6} Hz. Diagram of experimental data serves as the dependence Z"(Z'), where Z" – imagine resistance value and Z’ real resistance, or in other words impedance hodograph. On the basis of experimental data frequency dependence Z" and Z' the building of equivalent electric circuits for analyzing the structure of the samples was carried out.

The modulus of impedance was measured by Autolab in frequency range from 0,01 Hz to 1 MHz in temperature range 77–300K. The use of this method allows separating and identifying the contributions of various microstructure elements in the conductivity.

The low temperature studies of SOI-structures have been carried out in temperature range of 4,2-300K at magnetic fields up to 14T. The resistance at cryogenic temperatures has been measured in International Laboratory of High Magnetic Fields and Low Temperatures (Wroclaw, Poland). The samples have been cooled down to 4,2K 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



a

b

Fig. 1. The impedance dependence of imagine resistance value on real resistance (Z''=*f*(Z')) of nonrecrystallized polysilicon samples with carrier concentrations 2,4·10^{18} cm^{-3} (a) and 3,9·10^{19}cm^{-3} (b).

contacts of samples, the output of thermocouple and of the magnetic field sensor with the accuracy of upto 1×10^{-6} V.

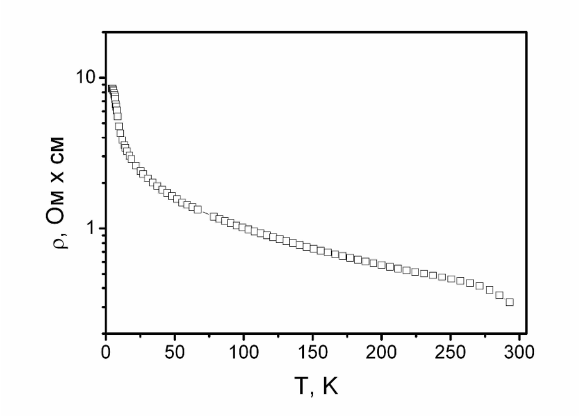
The Bitter-magnet based setup has been used to study the effect of strong magnetic fields on the samples. The induction of the magnet was 14T, deflection time 1,75 T/min and 3,5T/min at 4,2K and higher temperature range respectively.

II. Experimental results

The experimental results of nonrecrystallized polysilicon samples with carrier concentrations 2,4×10^{18}cm^{-3} and 3,9×10^{19}cm^{-3} are shown on hodographs (fig. 1).

As fololws from Fig.1, the hodograph dependence of nonrecrystallized polysilicon samples in SOI structures is linear that indicates in the presence of capacities mainly localized in grain barriers [3]. These results correspond to our previous research where the intrinsic features of polysilicon samples in SOI structures were found [4]. For example nonrecrystallized polysilicon layers with carrier concentration of 2,4×10^{18}cm^{-3} have a significant temperature dependence (fig.2) what indicates the presence of a large number of grain boundaries.

For nonrecrystalized poly-Si layers with charge carriers concentration of 2,4×10^{18}cm^{-3} the phenomena of negative magnetoresistance has been observed as well (Fig. 3). Together with the results of resistivity studies it is the evidence of hopping conductivity of polysilicon at low temperatures. As it seen from Figure 4 the conductivity of these samples in the low temperature range varies by the Mott law ~ρ(lnρ~T$^{-1/4}$).



a

Fig. 2. Temperature dependence of nonrecrystallized poly-Si layers with free charge carrier concentration of p_{300K} =2,4·10^{18} cm^{-3}.

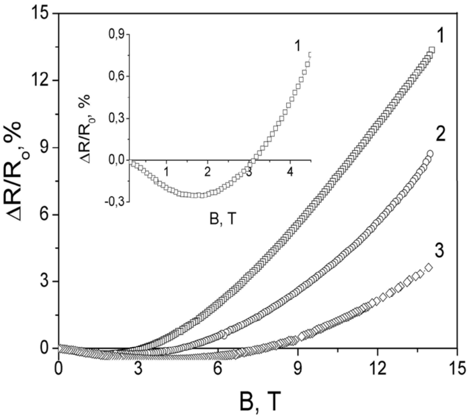


Fig. 3. Longitudinal magnetoresitance of unrecrystallized poly-Si layers with p_{300K}=2,4·10^{18}cm^{-3} at various temperatures: 1– 4,2K, 2– 9K, 3– 10,3K, 4– 19,2K. Inset: temperature dependence of magnetoresistance.

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 [5, 6]. 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 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

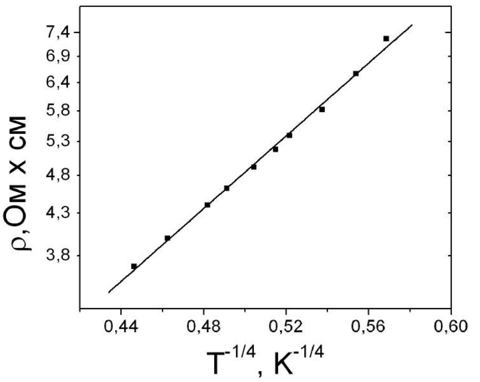


Fig. 4. Resistivity versus temperature for unrecrystallized poly-Si with charge carrier concentration p_{300K} =2,4·10^{18} cm^{-3}.

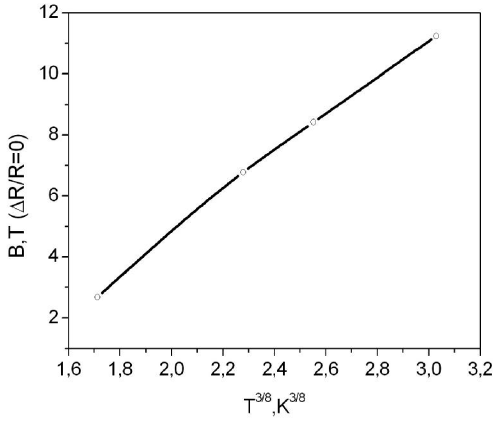


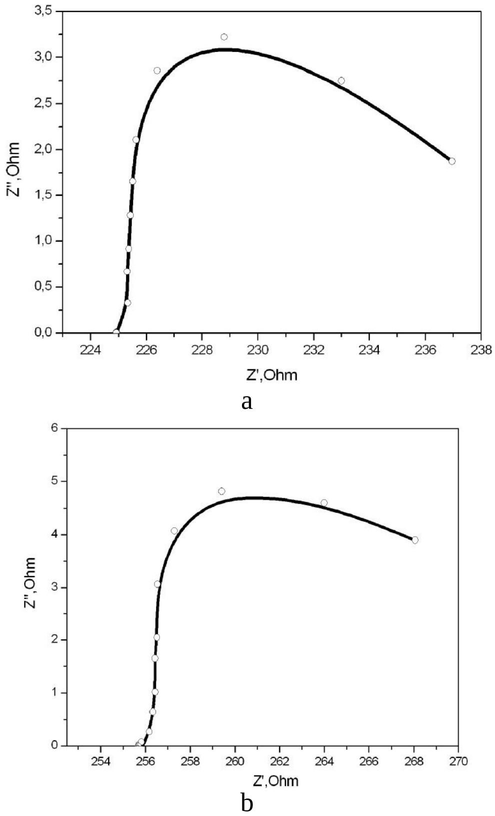
Fig. 5. Temperature dependence of magnetic field induction for unrecrystalized poly-Si layers with carriers concentration of p_{300K}= 2,4·$10^{18}$$cm^{-3}$.

potential profile, caused by the distortion of bands. That is why such a system should be considered as a very heaily 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 carriers percolation [6, 7].

As for now, there are experimental results that proved the satisfaction of the Mott law in heavily doped semiconductors. It has been shown [8] 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 [9] 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 [9], 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. 5). This fact confirms the Mott hopping conductivity at B=0.



a

b

Fig. 6. The impedance dependence of imagine resistance value on real resistance (Z''=f(Z')) of recrystallized polysilicon samples with carrier concentrations 4,8·10^{18} cm^{-3} (a) and 1,7·$10^{20}$$cm^{-3}$ (b)

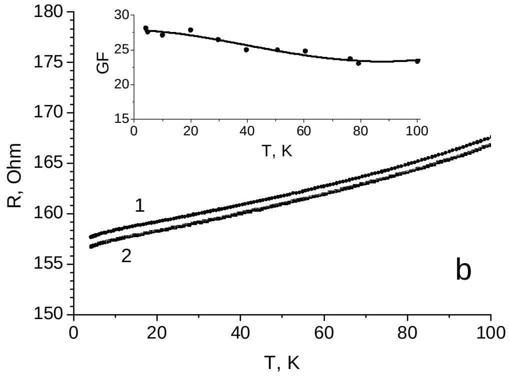


Fig. 7. Temperature dependences of resistance of strained (1) and unstrained (2) recrystallized poly-Si layers with carriers concentration of p_{300K}=1,7·10^{20} cm^{-3} ; inset – temperature dependence of strain gauge factor.

Studies of [10] show that the model of charge carriers capturing by traps on grain boundaries introduced by Seto is the most proper for accounting of grain boundaries influence on electronic properties of polycrystalline material [11]. This model suggests that due to defective structure the charge carrier traps appear in grain boundaries. This structure consists of disordered atoms of the main material that are dangling bonded to surroundings. Energy states of traps capture the part of charge carriers from ionized impurities, distributed in grain boundaries surrounding. Due to this process the average amount of free charge carriers in polycrystalline material decreases and the potential barrier in space-charge region arises. Therefore 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 the capturing of free charge carriers occurs. Besides it, 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 could be recommended to create microelectronic sensors on the basis of SOI-structures.

After laser recrystallization the hodograph curve obtained a semi-circle shape what indicates the increasing of homogenity of sample due to increasing the grain size (fig. 6).

For single-crystal sample (recrystallized polysilicon) the simplest equivalent circuit can be represented as parallel circuit capacity C and resistance R. In this case the impedance components are defined by:

$$Z' = R/(1+w^2R^2C^2),\ \ Z'' = \omega R^2C/(1+w\ R^2C^2),\ (2)$$

where *w=2p f,* the resistance *R* and the capacity *C* do not depend on frequency. In this case the impedance hodograph (Z’’=*f*(Z’)) have a semi-circle shape [12]. This confirms an assumption of increasing the homogenity of polysilicon in SOI structures due to laser recrystallization process.

As it has been shown in [4] heavily doped recrystallized polysilicon layers (p_{300K}=1,7×10^{20} cm^{-3}) show a metallic type conductivity, have rather high gauge factor (see fig.7.) as well as are the most stable in presence of magnetic field at 4,2 K.

Such polysilicon layers can be recommended to create piezoresistive mechanical sensors, operating at cryogenic temperatures and at the strong magnetic fields. At the same time the laser recrystallized polysilicon layers with carriers concentration of p_{300K} = 4,8×10^{18} cm^{-3} are better candidates for more accurate mechanical sensors for cryogenic temperatures about 4,2 K.

Conclusions

On the basis of complete studies of temperature dependence of conductivity, impedance analysis and magnetoresistance of polysilicon layers on dielectric substrates, the dominant nature of hopping conduction at low temperatures of nonrecrystallized samples with carrier concentration of p_{300K} =2,4×10^{18} cm^{-3} was established. In addition research show the nonrecrystallized polysilicon layers are characterized by high dispersion of material and conductivity is determined by contribution of grain boundaries. In the recrystallized polysilicon layers with carriers concentration of p_{300K} =1,7×10^{20} cm^{-3} it has been observed an increasing of material homogeneity, the presence of metallic type of electrical conductivity. These samples are the most stable in presence of magnetic field at 4,2 K and have a sufficiently great strain gauge factor as well. The results obtained evidence that recrystallizatized polysilicon layers can be recommended to create piezoresistive mechanical sensors operating at cryogenic temperatures and strong magnetic fields.

[1] A. Druzhinin, I. Maryamova, E Lavitska., et al. Laser recrystallized polysilicon layers for sensor application: electrical and piezoresistive characterization *// In Perspectives, Science and Technologies for Novel Silicon on Insulator Devices,* Eds. P.L.F.Hemment et al., Kluwer Acad. Publ. ,Dordrecht., pp. 127-135 (2000).

[2] A. Druzhinin, E. Lavitska, I. Maryamova, Y. Khoverko. Laser recrystallized SOI layers for sensor applications at cryogenic temperatures, in *Progress in SOI Structures and Devices Operating at Extreme Conditions.* F. Balestra et al. (Eds.). Kluwer Acad. Publ, pp. 233-237 (2002).

[3] E.Barsoukov, J.R. Macdonald. *Impedance spectroscopy: Theory, Experiment and Applications*, New York, Wiley ,pp.606 (2005).

[4] A. Druzhinin, I. Maryamova, I. Kogut et al. Polysilicon-on-insulator layers at cryogenic temperatures and high magnetic fields // *Science and Technology of SOI Structures and Devices Operating in a Harsh Environment*: ed. by D. Flandre et al., Dordrecht: Kluwer Academic Publishers., pp. 297-302 (2005).

[5] B.I. Shklovskii, A.L. Efros. *Electronic properties of doped semiconductors*, M.: Nauka,.pp 416 (1979) (in Russian)

[6] V.G. Kobka, R.P. Komirenko, Ju.V Konushin. et al. About conductivity of polycrystalline semiconductors // *Solid-state physics,***16**., pp. 2176-2178 (1982). (in Russian).

[7] B.I. Shklovskii Percolation theory and conductivity of heavily inhomogeneous mediums // *UFN*, **117**(3), pp.401-435 (1975). (in Russian).

[8] A.G. Zabrodskii Hopping conductivity and density step of localization states in the vicinity to Fermi level // *FTP.*, **11**(3), pp. 595-597 (1977). (in Russian).

[9] R.F. Konopleva. Galvanomagnetic properties of disordered semiconductors.// *Leningrad: Preprint LIJF*, pp. 25 (1980). (in Russian).

[10] N.C.–C. Lu, L. Gerzberg, C.–Y. Lu, J.D. Meindl. Modeling and optimization of monolithic polycrystalline silicon resistors // *IEEE Trans. Electron Devices*, **ED-28** (7), pp. 818-830 (1981).

[11] J. Seto The electrical properties of polycrystalline silicon films // *J.Appl.Phys.*, **46**(12), pp.5247–5254 (1975).

[12] A.I. Artamkin, A.A. Dobrovolskii, A.A. Vinkurov et al. Peculiarities of impurity states of vanadium in lead telluride // *Semiconductors*, **44** (12), (2010). (in Russian).