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Magnetic Properties of Silicon Doped with Impurity Atoms of Europium

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The electrical parameters of silicon samples diffusion doped by europium impurity atoms were studied by Van der Pauw (VDP) method. The experimental results were examined, particularly the surface morphology using an Atomic Force Microscope (AFM). The lattice constant of the materials was calculated with the help of Bragg-Brentano`s law using X-ray diffraction on the XRD pattern of the Si<P,Eu> sample.

Keywords: AFM, XRD, Bragg-Brentano, X-rays, Lattice constant, Miller index, Bragg angle.

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1. INTRODUCTION

Based on the results of research conducted by scientists and specialists on the formation of compounds of elements belonging to the lanthanides group in single crystalline silicon, the authors have revealed the possibilities of obtaining novel materials that can be used to create modern sensors and magnetic electronic devices [1-4]. The interest in this field is partially motivated not only by the chance to design the technology for obtaining new materials, but also to study their basic physical properties that still remains an urgent issue in the physics of semiconductors. Based on the scientific analysis of the literature, the observation of ferromagnetic state in silicon with dopants of lanthanide series of chemical elements is explained by the parallel arrangement of magnetic moments of dopant atoms in the crystal bulk. Since metals have a high concentration of electrons, it is relatively easy to control their spins. Semiconductor materials, particularly silicon, are diamagnetic materials. It was shown in work [5] that it is possible to change the magnetic properties of initial silicon by introducing the elements belonging to the lanthanides group with high spin ordering to silicon. The obtained results make it possible to apply the semiconductor silicon material in the creation of magnetic sensors for spintronic, for example, in the production of spin transistors There is an increasing interest in controlling its magnetic properties by introducing $4f$ group elements into silicon. The spin of $4f^7$ electrons in the outer electron shells of Eu atoms is equal to $S = 7/2$. It is of scientific and practical importance to study the magnetic properties of silicon by introducing Eu and dopant atoms.

2. METHODOLOGY

The dopant atoms of 99.999 % (product of Hebei Suoyi New Material Technology Co., Ltd.) chemically pure europium (Eu) metallic element selected as dopant atoms were diffused from the gaseous state into the initial n-type silicon. In this case, the relative resistance of the initial silicon $\rho = 6$; 40; 60 and 80 Ω·cm were selected and prepared with geometric dimensions of 8 × 4 × 1 mm^3. In an MG17-60/300 electric tube furnace, at a temperature of $T = 1200 \div 1350$ °C and in the interval of $t = 6 \div 15$ hours, the deposed atoms were diffused into the silicon from the gaseous state. After diffusion, the silicon samples were cooled by steady stepped cooling procedure. Due to the tiny diffusion coefficient of europium atoms, the penetration depth of lead atoms into silicon was small. In this case, it was found that the interstitial atoms are located in the lattice node instead of the reference silicon atoms in the crystal lattice of silicon single crystal [6, 7].

3. RESULT AND DISCUSSION

The electro physical parameters of silicon samples obtained after diffusion were studied using the ECOPIA HALL HMS-3000 device. The main goal of the research was to create and increase the concentration of clusters consisting of a combination of atoms on the surface of silicon. The larger the number of clusters of atoms on the surface of silicon are, the greater magnetic sensitivity of the sample will. The maximum solubility concentration of europium atoms in silicon is in the range of $N = 10^{18} \div 10^{19}$ cm $^{-3}$ [8, 9]. As a result of the experiment, the distribution of the concentration of europium atoms in silicon was obtained (Fig. 1) as follows.

$$C(x,t) = C_0 erfc\left(\frac{x}{2\sqrt{Dt}}\right). \tag{1}$$

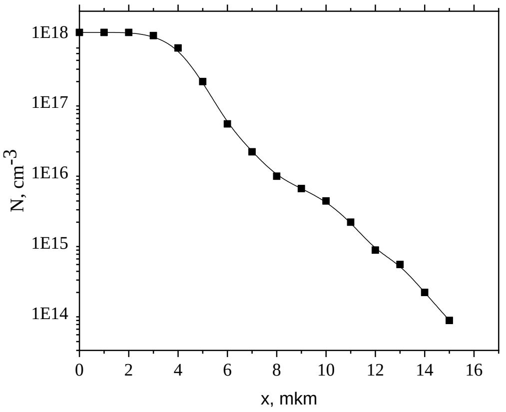


Fig. 1 – Distribution of the concentration of europium dopant atoms on silicon surface and subsurface layer

Table 1 – Data on electro physical parameters after diffusion of europium atoms into silicon single crystal are given in

Samples	Conductivity type	Resistivity of reference sample; ρ, Ω·cm	Mobility of charge carriers; μ, cm^2/V·s	Concentration of current carriers; N, cm^{-3}
KEF* – 80	n	73	1077	$7,9 \cdot 10^{13}$
KEF – 40	n	38,6	978	$1,65 \cdot 10^{14}$
KEF – 6	n	6,93	571	$1,1 \cdot 10^{15}$
Si<Eu> KEF – 80	p	0,018	191	$1,8 \cdot 10^{18}$
Si<Eu> KEF – 40	p	0,0136	204	$2,24 \cdot 10^{18}$
Si<Eu> KEF – 6	p	0,12	309	$1,26 \cdot 10^{17}$

* *KEF – phosphorus doped silicon*

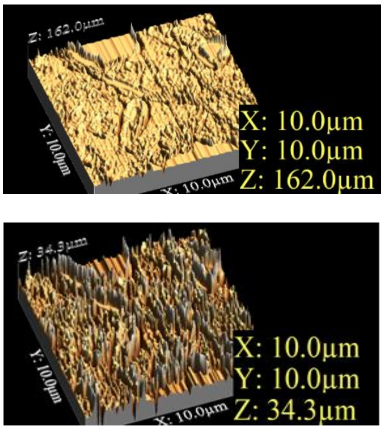


Fig. 2 – Images of the surface condition of Si<P,Eu> samples obtained in AFM

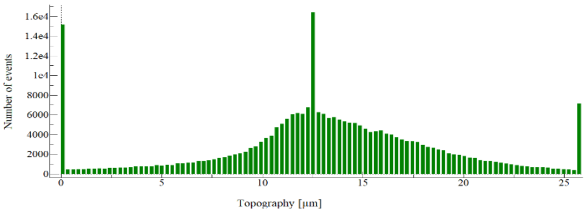


Fig. 3 – Si<P,Eu> samples in AFM peaks formed by intervening atoms in the length range of 0 ÷ 25 µm

The study of the positions of atoms on the surface of silicon samples doped with europium impurity atoms was carried out using an atomic force microscope (AFM) installed at Ege University (Izmir, Turkey). AFM provides information and images on position of atoms on the surface of the material. In AFM, the electric field of the conducting surface potential allows measuring the magnetic domains. There are three main methods for measuring the height of the charge state of atoms in the images obtained in the AFM, histogram analysis, one point at the top and bottom of the surface structure, and a line corresponding to its top and bottom [11].

Another interesting way to analyze AFM images obtained by scanning a small controller on the surface of a silicon sample doped with europium doped atoms using AFM is to provide information on the number of atoms in the resulting peaks. The number of atoms in the cluster corresponding to the peak observed in the spectrum of 12.5 µm on the surface of the silicon in the image obtained by AFM was $1,6 \cdot 10^4$ (Fig. 4).

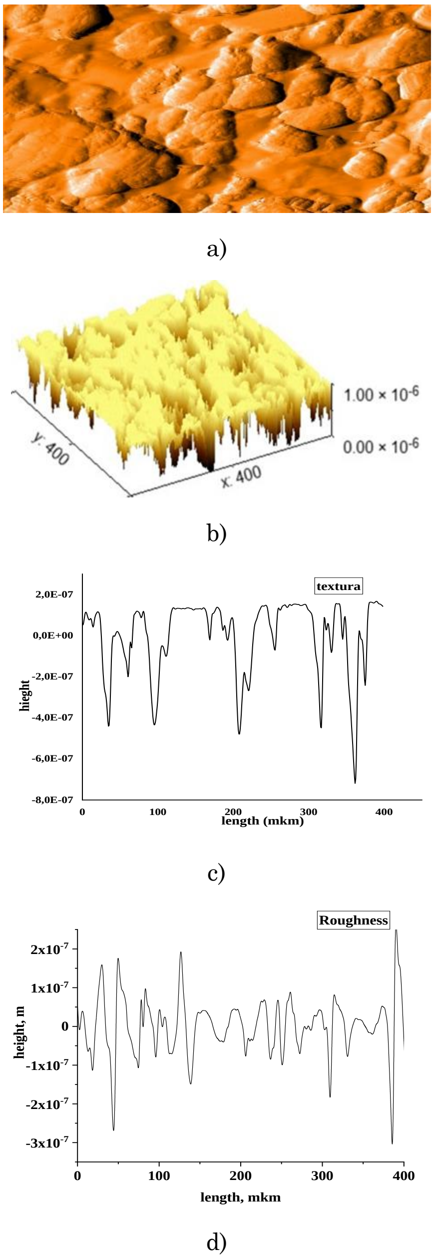
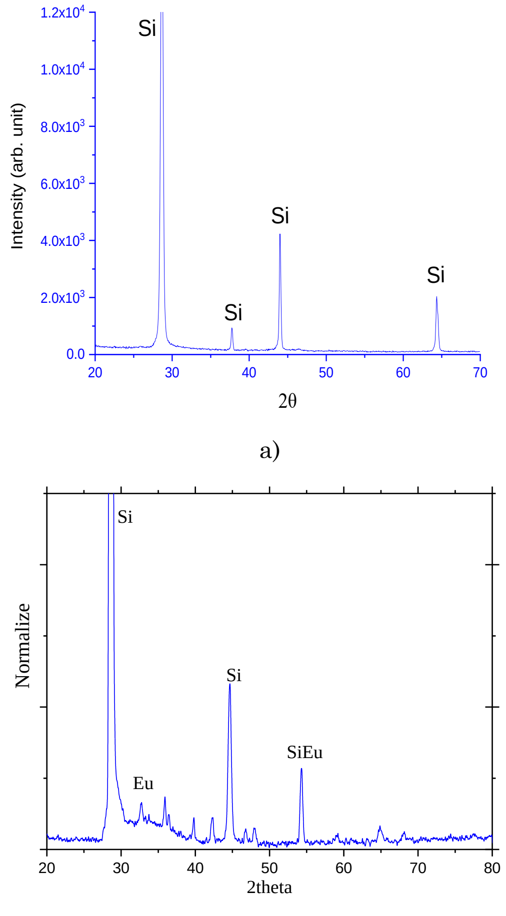


Fig. 4 – Data determined on the basis of gwyddion software analysis of the results obtained in the AFM of the Si<P,Eu> sample. a) morphology of the sample surface, b) 3D image of the sample, c) texture of the sample surface, d) degree of roughness of the sample surface

During the study of the silicon surface by AFM, samples with a size of 400 × 400 µm and a thickness of 1 µm were selected and the morphology of the surface structure was studied.

According to the information in the scientific literature, it was determined that the crystal structure of europium is R-shaped, and the lattice constant is equal to 5.144 Å [12, 5]. Investigation of the lattice constant of silicon samples obtained after diffusion was carried out using X-ray diffraction.



a)

b)

Fig.5 – X-ray diffraction (XRD) a) diffractogram of Si<P> sample b) diffractogram of silicon doped with europium atoms

Periodically ordered structures can be studied at the atomic scale using X-ray diffraction. The XRD method is used to study the structure of monocrystalline or polycrystalline materials. Based on the *X*-ray diffraction produced by this method, structural changes in the silicon crystal lattice can give an opportunity to determine. The rays emitted from the *X*-ray tube pass through the silicon sample and are reflected on the screen and fall on the detector. Scattered X-rays are subsequently added to each other. The diffraction image formed in this combination is used to determine the structural composition of materials using Bragg`s law [13]. The following formula is used to calculate the distance in the crystal lattice using Bragg's law:

$$n\lambda = 2d_{hkl}\sin\theta. \qquad (2)$$

In this case, the distance between the crystal lattice and the lattice constant references in the following way:

$$d_{hkl} = \frac{n\lambda}{2\sin\theta}, \qquad (3)$$

$$a = d_{hkl}\cdot\sqrt{h^2+k^2+l^2}. \qquad (4)$$

Fig. 5 shows the structure of the crystal lattice of silicon samples with europium interstitial atoms. $2\theta = 28{,}30°$ of X-ray signals 44,64°; and the peaks at 64,86° belonged to the planes in the silicon lattice in the [14] crystal direction. Signals related to EuO compound $2\theta = 30{,}1°$; gave peaks. Based on the analysis of experimental results, the size and lattice constant of the formed impurity atom cluster were determined (Table 2).

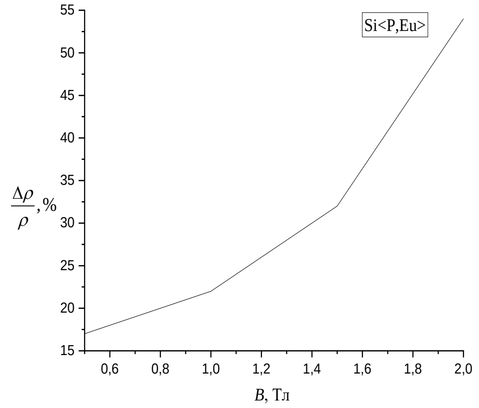


Fig. 6 – Magnetic resistance as a function of magnetic field in p-type Si<P,Eu> samples

$$\rho = \frac{U_v \cdot S}{I \cdot l}. \qquad (5)$$

The Hall method is used to determine the magnetic resistance of the sample, here: U_v – the voltage between the probes, S – the surface of the sample, current flowing through the I –sample, l – the length of the sample.

The magnetic resistance of the samples is described by the following expression:

$$\frac{\Delta\rho}{\rho} = \frac{\rho_B - \rho}{\rho}. \qquad (6)$$

We relate this given formula of magnetic resistance to the current flowing through the field.

$$\frac{\rho_B - \rho}{\rho} = \frac{I - I_B}{I_B}, \qquad (7)$$

here is ρ_B – the relative resistance of the sample in the magnetic field; ρ – the magnetic field-free dependence of the resistivity in the sample; I_B – the magnetic field of flowing current in the sample; I – the magnetic field-free of flowing current in the sample:

In the graph shown in Figure 6 above, it can be seen that the magnetoresistance property of Si<P,Eu> has increased by $B = 0 - 2\,Tl$, $T = 300\,K$, $\Delta\rho/\rho = 54\%$.

Table 2 – The size and lattice constant of the formed impurity atom cluster of Si<P,Eu>

The element name	Wave length λ, (Å)	Miller index, *hkl*	Bragg angle θ, (degree)	Intermediate distance, d_{hkl}, (Å)	The constant of the lattice, a, (Å)
Si	1,5406	111	14.15	2,9666	5,1382
EuO	1,5406	111	15.05	3,1510	5,445

4. CONCLUSIONS

The analysis of the above experimental results shows that when europium impurity atoms are diffused into silicon in gaseous state, the clusters consisting of europium impurity atoms are formed on the surface and subsurface layer of silicon. The clusters of the formed europium impurity atoms alter not only the electro physical parameters of the obtained material, but also the properties of the magnetic sensitivity.

The obtained scientific results in the research of the electro physical and magnetic properties of silicon with europium impurity atoms complement the scientific data in the research of the physical mechanism of the formation of deep energy levels, and also on widen the basis of the obtained samples (Si<P,Eu>) allow the creation of magnetic sensors with high electromagnetic sensitivity in spintronic.

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Магнітні властивості кремнію, легованого домішковими атомами європію

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Методом Ван-дер-Пау (ВДП) досліджено електричні параметри дифузійно легованих атомами європію зразків кремнію. Експериментальні результати, зокрема морфологію поверхні, досліджували за допомогою атомно-силового мікроскопа (АСМ). Стала ґратки матеріалів була розрахована за допомогою закону Брегга-Брентано з використанням рентгенівської дифракції на рентгенограмі зразка Si<P,Eu>.

Ключові слова: AFM, XRD, Брегг-Брентано, Рентгенівське випромінювання, Стала ґратки, Індекс Міллера, Кут Брегга.