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Influence of Infrared Radiation on the Magnetic Properties of Silicon with Nanoclusters of Manganese Atoms

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Abstract The paper reports the effect of quenching of negative magneto-resistance in the presence of infra-red light in the range λ = 1,2 ÷ 3 µm in silicon samples doped by manganese. The paper also shows, that in contrast to other magnetic semiconductor materials, in silicon samples with nanoscale clusters of manganese atoms, the value of negative magneto-resistance can increase substantially due to electric and magnetic fields and temperature variation. Silicon with nanoclusters of manganese atoms could be used for designing a novel class of photo-magnetic sensitive devices operating in the infrared region.

Keywords Magnetic nanoclusters, Manganese, Infrared, Negative magneto-resistance

1. Main

On the basis of new discovery made by authors (i.e. phenomenon of quenching of negative magneto-resistance (NMR) by infra-red (IR) light, it had been experimentally revealed that, in silicon samples with magnetic nanoclusters at temperature T = 300 K in the range of small values of the electric field E≤20 V / cm, and by varying wavelength of the infrared radiation in the range of λ = 1,2 ÷ 3 micron, one can control in the wide range the value of negative magneto-resistance. In samples with resistivity ρ=5·10^3 Ω·cm, the authors have been able to detect maximum value of negative magneto-resistance, i.e. with the increase of incident photon energy, the value of negative magneto-resistance significantly reduces and at $h\nu$ =1 eV, negative magneto-resistance dropped more than 30 fold.

Unlike other semiconductor materials doped with paramagnetic impurity atoms [1, 2], silicon with nanoclusters of manganese atoms [3] has anomalously high negative magneto-resistance (NMR) at ambient temperature [4].

In [5] it has been shown, how the value of negative magneto-resistance could be varied over a wide range by means of external electric field and temperature, as well as by varying the electrical parameters of silicon samples doped with boron and manganese. The study of influence of both impurity concentration and background light on the behavior of the magneto-resistance in silicon samples doped with boron and manganese is of great practical interest.

Such research does allow not only controlling the value of magneto-resistance in samples in the infrared region, but also create a novel class of more sensitive photo-magnetic devices based on them. Analysis of published studies suggests that the influence of the wavelength of the infrared - light on magnetic properties, especially on NMR is not sufficiently studied. In [6], the authors have shown that the conductivity in structures: Si:BC with blocking layer in the conduction band depends essentially on the ambient light. The dependence of the photoconductivity on the magnetic field in this case is observed at a temperature T = 4,2-9 K and value of the magnetic field B = 0 ÷ 30 Tesla.

2. The Technique of Experiment

The aim of this work is the study of negative-magnetoresistance in silicon samples with nanoclusters of manganese atoms as a function of the wavelength of the incident light λ = 1,2 ÷ 3 micron, the light power 5·10^{-5} W/cm^{-2}, at room temperature in the presence of the magnetic field B = 0 ÷ 2 Tesla. Such studies allow not only to detect the magnetic properties of silicon with nanoclusters of manganese atoms but also to determine the possibility of their practical application in creating photo-magnetic devices, as well as to develop new scientific direction called “IR – spintronics”.

For obtaining samples containing silicon nanoclusters with required concentration, single crystalline p- type silicon was used as the starting material with a resistivity of ρ=3

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Ω·cm ($p=7\cdot10^{15}$ cm^{-3}). Doping of silicon with manganese was carried out by the technique developed by authors [4].

Doping conditions were chosen so as to obtain samples with different specific resistances in the range of $\rho=8\cdot10^{2}\div10^{5}$ Ω·cm at T = 300 K. All samples had *p- type* conductivity. Also samples were made with the same electrical parameters doped with manganese without forming clusters by conventional high temperature technique [7].

The task-specific equipment (Infra-red spectrometer-IKS 21), which allows varying electric and magnetic fields, temperature and wavelength of infrared radiation and its power was designed. To prevent the background and incident light fall in cryostat window, as well as after infra-red irradiation emitter (light source) of IKS-21, the filters were used that were made out of polished silicon with thickness d = 400 μm. Virtually all of the samples have had the same size (0,08x 0,4x 1 cm^3) and were handled under identical conditions, both before and after the diffusion.

The relative change in NMR in samples calculated on the basis of expression $\left[\left(\frac{\Delta\rho}{\rho}\right)_{dark}\Big/\left(\frac{\Delta\rho}{\rho}\right)_{h\nu}\right]$ (where $\left(\frac{\Delta\rho}{\rho}\right)_{h\nu}$ - NMR in samples at infrared light with energy hv, whereas $\left(\frac{\Delta\rho}{\rho}\right)_{dark}$ - NMR in samples, when infrared radiation is absent (in similar experimental conditions) as a function of energy of incident photons of infrared radiation shown on Fig. 1.

As can be seen from Fig. 1 the effect of IR light on MR essentially depends on the resistivity of the sample. In samples where there is a maximum of NMR with $\rho=5\cdot10^{3}$ Ω·cm (at T = 300 K), NMR begins to decrease, i.e., IR quenching of NMR occurs (IRQ) of NMR at 0,3 eV, while the further increase in IR photon energy increases the effect of quenching.

At light with energy of photons hv> 0,7 eV, the process significantly increases and at hv = 1 eV, the NMR value decreases 30-fold (Curve 2, Fig. 1), i.e., there is a unique phenomenon - managing magnetic properties of Si with nanoclusters of manganese atoms by varying the wavelength of the infrared radiation, which otherwise cannot be obtained by other external influences (temperature and electric field) [4, 5].

With an increase in the resistivity of the samples, the NMR value decreases, respectively [4] and the effect of IRQ also weakens, whereas in overcompensated samples only the effect of positive magnetic resistance (PMR) occurs [4], the influence of the infrared light on MR samples is practically absent (curves 3,4,5).

A similar situation manifests for samples with $\rho<5\cdot10^{3}$ Ω·cm, where the value of NMR decreases with decreasing resistivity, respectively. In these samples, the effect of infrared light is significantly weakened. Thus, it was found that the maximum impact of IR - light on the value of NMR takes place in the Si <B, Mn> samples of the p-type with $\rho\sim(4\div6)\cdot10^{3}$ Ω·cm.

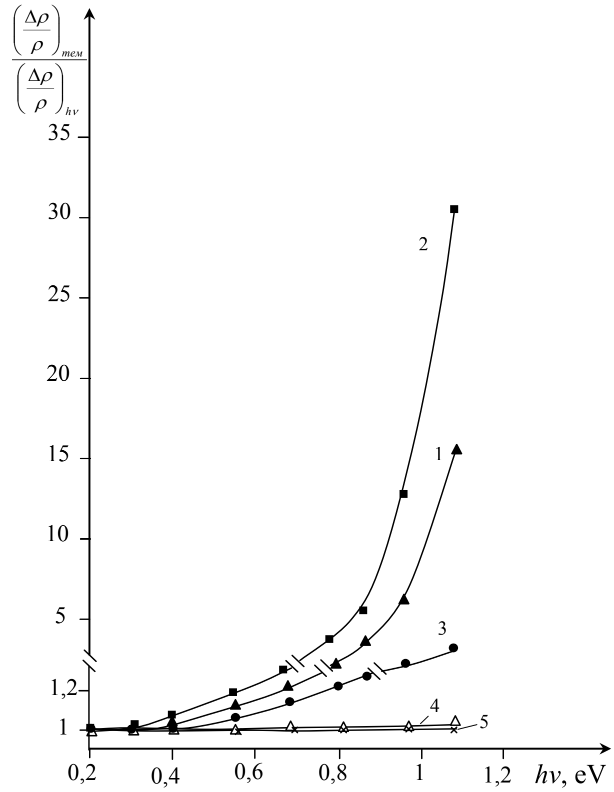

Figure 1. Spectral dependence of reduction ratio of NMR under the influence of IR-light $\left(\frac{\Delta\rho}{\rho}\right)_{h\nu}$, relative to dark value of NMR $\left(\frac{\Delta\rho}{\rho}\right)_{dark}$ in samples *p* -Si<B,Mn> with various resistivity at E=20 V/cm, B=1,7 Tl, T=300 K. 1) $2,2\cdot10^{3}$ Ω·cm *p*-type, 2) $5\cdot10^{3}$ Ω·cm *p*-type, 3) $4\cdot10^{4}$ Ω· cm *p*-type, 4) $1,2\cdot10^{5}$ Ω·cm *p*-type, 5) 10^{4} Ω·cm n-type

Interesting results have been found in the course of study of simultaneous exposure of samples to infrared radiation and electric field and their influence on magnetic properties of the samples at T = 300 K. It was revealed that, at low values of the electric field with increasing electric field, the influence of infrared radiation on NMR is significantly enhanced reaching its maximum value at E = 20 V / cm (Fig. 2, curve 2).

Further increase of the electric field leads to a significant weakening of the influence of infrared light on NMR and E = 100 V / cm and at hv = 1 eV, the influence of IR light is decreased almost 6 ÷ 7 fold (Fig. 2, curves 3,4,5). These results show that at low values of the electric field is stimulated by the influence of IR radiation, i.e. IRQ of NMR increases, and starting from E≥20 V/cm, the electric field and IR radiation act against each other and E≥150 V / cm the influence of infrared light is almost completely suppressed, and magnetic properties of the material are determined solely by the electric field. This pattern holds for all samples regardless of the resistivity and in the entire region of photons of infrared radiation energy.

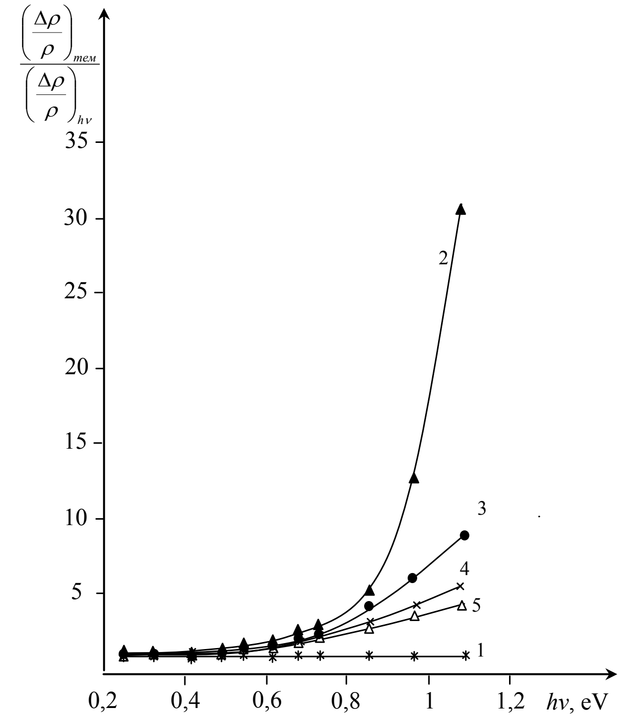

Figure 2. Spectral dependence of reduction ratio of NMR under the influence of IR-light $\left(\frac{\Delta\rho}{\rho}\right)_{h\nu}$, relative to dark value of NMR $\left(\frac{\Delta\rho}{\rho}\right)_{dark}$ in samples p -Si<B,Mn> with $\rho=5\cdot10^3$ Ω·cm, T=300 K, B=1,7 Tl, at various electric fields 1) 2 V/cm, 2) 20 V/cm, 3) 50 V/cm, 4) 80 V/cm, 5) 100 V/cm

Studies have shown that, in the samples doped with manganese without forming clusters regardless of their specific resistance in the investigated region of photon energies and the electric field there is no appreciable change in their magnetic properties. On the basis of these results, one can state that the infrared light does practically not affect MR in samples, and mainly affects the NMR, which is explained by presence of magnetic nanoclusters.

The analysis of the results showed that in contrast to other magnetic semiconductor materials, in silicon samples with nanoclusters of manganese atoms NMR value can increase substantially under the influence of electric and magnetic fields and temperature [4, 5].

It was established experimentally that in silicon samples with magnetic nanoclusters at temperature T = 300 K in the region of small values of the electric field E≤20 V / cm, by varying the wave length of the infrared radiation in the range of λ = 1,2 ÷ 3 μm, NMR value can be controlled in the wide range.

3. Conclusions

By exposing samples to infrared radiation one can reduce the NMR value 30-fold by varying the wavelength, and at higher powers of infrared radiation one can also observe inversion of the mark, i.e., negative to positive magnetic resistance (PMR). Thus, by choosing the optimum values of the wavelength of infrared light and of electric field one can selectively control the magnetic properties of such materials.

In this regard, silicon with nanoclusters of manganese atoms is a unique material for not only designing a new class of performance photo-magnetic sensitive devices operating in the infrared region, but also for developing new scientific direction of IR - spintronics.

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