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# Spintronic devices based on magnetic nanostructures

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Two types of spintronic devices on the basis of magnetic nanostructures containing silicon dioxide films with cobalt nanoparticles $SiO_2(Co)$ on GaAs substrate, magnetic sensors and magnetically operated field-effect transistor, were studied. Action of magnetic sensors is based on the injection magnetoresistance effect. This effect manifests itself in avalanche suppression by the magnetic field in GaAs near the $SiO_2(Co)/GaAs$ interface. Field-effect transistor contains $SiO_2(Co)$ heterostructure under gate. It was found that the magnetic field action leads to significant changes in electron mobility in the channel due to interaction between spins of Co nanoparticles and electron spins.

Исследованы два вида спинтронных устройств на основе магнитных наноструктур, содержащих пленки диоксида кремния с наночастицами кобальта $SiO_2(Co)$ на подложке GaAs — магнитных сенсоров и магнитоуправляемого полевого транзистора. Действие магнитных сенсоров основано на эффекте инжекционного магнитосопротивления, который заключается в том, что магнитное поле подавляет лавинный процесс в GaAs вблизи интерфейса $SiO_2(Co)/GaAs$. Полевой транзистор содержит гетероструктуру $SiO_2(Co)$ под затвором. Обнаружено, что благодаря эффекту взаимодействия спинов наночастиц Co со спинами электронов канала, магнитное поле приводит к существенному изменению подвижности электронов.

## 1. Introduction

Operation of carrier spins in ferromagnetic/semiconductor heterostructures offers enhanced functionality of spin-electronic devices such as spin transistors, sensors, and magnetic memory cells [1, 2]. This manipulation can be realized on the basis of magnetic nanostructures by use of magnetoresistance effects and due to interactions between magnetic nanostructures and electron spins in field-effect transistors. Magnetoresistance effects are attracting much attention in a view of their various applications. An extremely large magnetoresistance ($10^5$ %) has been observed at room temperature in GaAs/granular film heterostructures in the avalanche state, in which a granular film contains ferromagnetic metal nanoparticles or ferromagnetic islands on semiconductor interface. The value of this effect is two-three orders higher than the maximum values of the giant magnetoresistance in the metal magnetic multilayers and the tunnelling magnetoresistance in the magnetic tunnel junction structures. Magnetoresistance effects of high values have been found in GaAs/granular film heterostructures with granular films containing ferromagnetic metal MnSb nano-islands [3, 4] and ferromagnetic MnAs clusters [5]. The high values of the magnetoresistance based on the avalanche breakdown has been observed in the $SiO_2(Co)/GaAs$ heterostructures, in which SiO$_2$(Co) is the granular SiO$_2$ film containing Co nanoparticles [6–9]. This effect has been called the injection magnetoresistance (IMR). It appears, when electrons are injected from the granular film into the GaAs.

Field-effect high electron mobility transistor (HEMT) devices with spin polarized electron channels are promising due to the possibility to change electron spins in channels by magnetic field action. In this paper, we studied devices based on magnetic nanostructures with silicon dioxide films with cobalt nanoparticles SiO$_2$(Co) on GaAs substrate — magnetic sensors and magnetically operated field-effect transistor. Magnetic sensors are based on the IMR effect. The field-effect transistor contains SiO$_2$(Co) heterostructure under gate. The magnetic field action leads to significant changes in the electron mobility in the channel due to interaction between spins of Co nanoparticles and electron spins.

## *2. Giant injection magnetoresistance and magnetic sensors*

High values of the IMR-effect in the SiO$_2$(Co)/GaAs heterostructures are explained by the magnetic-field-controlled process of impact ionization in the vicinity of the spin-dependent potential barrier formed in the semiconductor (Fig. 1). The spin-dependent potential barrier is formed near the interface by an exchange interaction between the electrons in localized states in the electron accumulation layer in the semiconductor and $d$-electrons of Co [8, 10]. The avalanche process is induced by electrons, which (1) surmount over the spin-dependent potential barrier formed by exchange-splitted localized states and (2) tunnel from the localized states. The impact ionization induced by the injected electrons produces holes, which move, are accumulated in region of the potential barrier and lower the barrier height [8]. Owing to the formed hole feedback, small variations in the barrier height lead to significant changes in the current and in the avalanche process. Applied magnetic field increases the barrier height, reduces the transparency of the barrier, and suppresses the onset of the impact ionization.

Magnetic sensors were produced on the samples SiO$_2$(Co)/GaAs with the $n$-GaAs substrates. Carrier concentrations in the $n$-GaAs are equal to $10^{15}$ cm$^{-3}$. The SiO$_2$(Co)

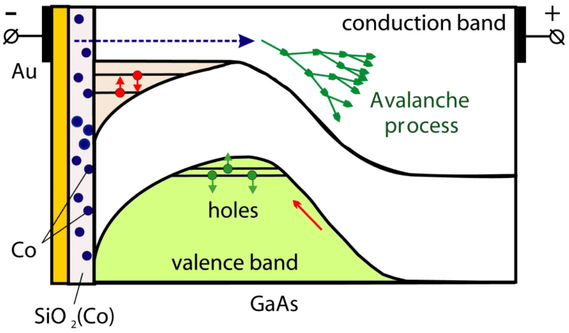

Fig. 1. Schematic energy band diagram of the magnetoresistive sensor based on the heterostructure with a quantum well near the interface and a hole trap in the avalanche regime.

films were deposited by the ion-beam co-sputtering of the composite cobalt-quartz target onto the GaAs substrates heated to 200°C. The concentration of Co nanoparticles in silicon dioxide was varied by changing the ratio of target areas of cobalt and quartz areas. The film composition was determined by the nuclear physical methods of element analysis using a deuteron beam of the electrostatic accelerator (Rutherford backscattering spectrometry and nuclear reaction with oxygen). For the samples used in magnetic sensors, a relative Co content is in the range of 45–71 at.% and film thickness is 40 nm. An average size of Co particles, determined from the low-angle X-ray scattering measurements, increases with Co content: from 2.9 nm at 45 at.% to 3.9 nm at 71 at.%. As the Co content increases, the resistivity of the SiO$_2$(Co) films decreases from 0.3 $\Omega \cdot$ cm (45 at.%) through $3.0 \cdot 10^{-3}$ $\Omega \cdot$ cm (60 at.%) to $1.4 \cdot 10^{-3}$ $\Omega \cdot$ cm (71 at.%). Protective Au layer of a thickness 3–5 nm have been sputtered on SiO$_2$(Co) films.

Sizes of the samples in magnetic sensors were equal to $3 \times 3 \times 0.4$ mm$^3$. One contact was on GaAs substrate, and the other one — on Au layer sputtered on the granular film. Magnetic sensors are characterized by the injection magnetoresistance, which is defined by the coefficient

$$IMR = \frac{R(H) - R(0)}{R(0)} = \frac{j(0) - j(H)}{j(H)},$$

where $R(0)$ and $R(H)$ are the resistances of SiO$_2$(Co)/GaAs heterostructure without a field and in the magnetic field $H$, respectively; $j(0)$ and $j(H)$ are the current densities flowing in the heterostructure in the

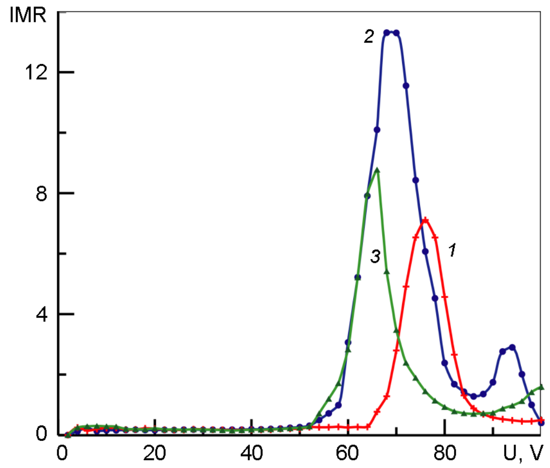

Fig. 2. Injection magnetoresistance ratio, of magnetic sensors versus the applied voltage $U$ in the magnetic field $H = 2.1$ kOe for $SiO_2(Co)/GaAs$ heterostructures with Co concentrations: *1* — 54 at.%, *2* — 60 at.%, *3* — 71 at.%.

absence of a magnetic field and in the field $H$. The IMR ratio for $SiO_2(Co)/GaAs$ heterostructures with different Co concentrations versus the applied voltage $U$ in the magnetic field $H = 2.1$ kOe at room temperature is shown in Fig. 2. The magnetic field $H$ is parallel to the film. For magnetic fields of high values (>10 kOe) the IMR coefficient increases with the growth of the applied voltage [8]. In contrast to this, for low magnetic fields the IMR reaches the highest values in the region of avalanche onset. As one can see from Fig. 2, in order to reach high sensitivity of sensors it is need to apply the voltage in this region.

## 3. Magnetically operated field-effect transistor

The field-effect HEMT device with a spin polarized electron channel was developed on the basis of the $n$-type $GaAs/Al_{0.27}GaAs_{0.73}/In_{0.18}Ga_{0.82}As$ heterostructures grown on semi-insulator GaAs substrates (Fig. 3). Two-dimensional electron gas is formed at $Al_{0.27}GaAs_{0.73}/In_{0.18}Ga_{0.82}As$ interface. Highly mobile conducting electrons with very high concentration in two-dimensional electron gas form the channel with very low resistivity. This device contains an amorphous granular $SiO_2(Co)$ film with cobalt nanoparticles under the gate electrode. Thickness of the granular film is equal to 40 nm. An average size of Co particles is about 3.5 nm. $SiO_2(Co)$ film polarizes electron spins in the channel under the gate.

Current-voltage curves of field-effect devices have two different parts [11]. If the voltage between the source and the drain $U_{sd}$ is less than the saturation voltage $U_{sd}^{(sat)}$, then the current-voltage curve is sublinear and the current $J$ flowing in the channel is determined as

$$J = \frac{\mu C b}{l}\left[(U_{gs} - U_{gs}^{(thr)})U_{sd} - \frac{1}{2}U_{sd}^{2}\right], \qquad (1)$$

where $U_{gs}$ is the voltage between the gate and the source, $U_{gs}^{(thr)}$ is the threshold voltage between the gate and the source, when there is no current in the channel, $C$ is the specific capacity between the gate and the channel, $\mu$ is the electron mobility, $b$ and $l$ are the channel width and the length, respectively. When $U_{sd} = U_{sd}^{(sat)}$, the channel becomes blocked at the drain contact and an

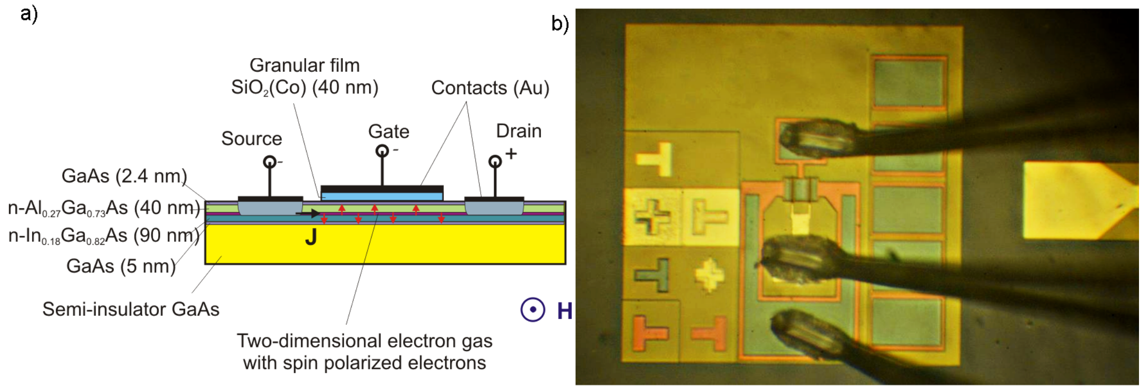

Fig. 3. Field-effect HEMT device with spin polarized electron channel under gate electrode. (a) Schematic structure, (b) topology of contacts.

electrical field of high values appears in this region. In this case, the saturation voltage is

$$U_{sd}^{(sat)} = U_{gs} - U_{gs}^{(thr)}.$$

For $U_{sd} \ge U_{sd}^{(sat)}$ the drain current $J$ is weakly dependent on the voltage $U_{sd}$ and the current-voltage curve can be approximated by a line with a weak slope. In the first approximation this sloping part of the current-voltage curve can be written as

$$J = \frac{\mu C b}{2l}\left(U_{gs} - U_{gs}^{(thr)}\right)^2. \qquad (2)$$

The current-voltage dependences of the developed field-effect HEMT structure (Fig. 4) contain two parts of the current-voltage curve described by relations (1) and (2). The saturation voltage is in the range 0.4–0.7 mV. As one can see from Fig. 4, the drain current of the field-effect transistor presents strong dependence on the governed external magnetic field $H$. The electron mobility $\mu$ in the channel decreases with the growth of the applied magnetic field. This property can be used in magnetosensitive devices.

## 4. Conclusions

We studied devices based on magnetic nanostructures containing silicon dioxide films with cobalt nanoparticles $SiO_2$(Co) on GaAs substrate — magnetic sensors and field-effect transistor. Magnetic sensors are based on the injection magnetoresistance effect at the avalanche onset regime. The field-effect transistor contains $SiO_2$(Co) film under gate. The both structures exhibit high magnetic sensitivity at room temperature.

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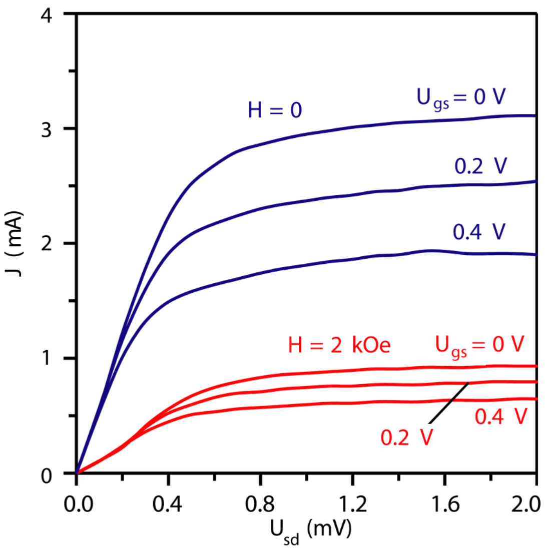

Fig. 4. Current-voltage dependences of the field-effect HEMT device in the magnetic field $H$ = 2 kOe and without a magnetic field. $U_{sd}$ is the drain voltage, $U_{gs}$ is the voltage at the gate electrode.

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# Спінтронні пристрої на основі магнітних наноструктур

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Досліджено два види спінтронних пристроїв на основі магнітних наноструктур, що містять плівки діоксиду кремнію з наночастинками кобальту $SiO_2(Co)$ на підкладці GaAs — магнітних сенсорів і магнітокерованого польового транзистора. Дія магнітних сенсорів заснована на ефекті інжекційного магнітоопору, який полягає у тому, що магнітне поле пригнічує лавинний процес в GaAs поблизу інтерфейсу $SiO_2(Co)/GaAs$. Польовий транзистор містить гетероструктуру $SiO_2(Co)$ під затвором. Виявлено, що завдяки ефекту взаємодії спинів наночастинок Co зі спинами електронів каналу, магнітне поле призводить до істотної зміни рухливості електронів.