Technology features of creating InSb-based spin-valve

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Abstract. Technological route is reported how to fabricate an InSb spin device for studying spin-transport phenomena in CPP geometry. The device, which consists of ferromagnetic CoFe layer and MgO tunnel barrier deposited on the n-InSb single-crystal substrate, was manufacturing by method of contact photolithography with lift-off technology of drawing transfer in the topological layers. The optimal methods for preparation of InSb substrate surface and photoresist exposure parameters are found by measuring the voltage between InSb and ferromagnetic probe (Hanle effect) that appears due to the spin polarization of electrons injected from ferromagnet into InSb.

1. Introduction
Information technologies, i.e. methods and devices for collection, storage and distribution of information, needs permanent development and improvement. Spin electronics (spintronics) uses not only charge of electron but also its spin. The development of devices in which information is coded with the electron spins should lead to creation of the new generation of devices in which the ordinary microelectronics and spintronics are integrated.

Of special interest are semiconductor devices in which injection and detection of spin-polarized electrons are realized. Si and GaAs were used in such spintronic devices [1,2]. Other interesting semiconductor is indium antimonide (InSb), which is characterized by high electron mobility (about $10^6$ cm$^2$/V·s) at temperature of 77 K and the spin diffusion length of 25 μm at T=77 K [3]. In InSb-based devices the electrical injection and detection of spin-polarized electrons were also realized [3,4]. These devices were composed of metallic and dielectric layers deposited on InSb substrate by magnetron sputtering. The ferromagnetic contacts, conductive tracks and contact pads were produced by method of contact photolithography with lift-off technology of drawing transfer in the topological layers. Our article is devoted to some features of technology of fabrication of these lateral spin devices.

2. Fabrication of spin device
Figure 1 shows the photos of the spin device taken with a stereoscopic microscope (SM) and with a scanning electron microscope (SEM). The fabrication technology implies several operations, namely, insulating layer formation, creation of the tunnel barrier and ferromagnetic contacts, creation of the conductive tracks and contact pads, formation of a protective layer.
Figure 1. A photo of an InSb-based spin device: the central vertical strip is the n-InSb - semiconductor channel in the photoresist layer, it is crossed by six horizontal ferromagnetic strips, whose composition is described in the text, to which the transitional contacts are terminated, ending with contact pads: a) - general view (SM); b) and c) - a photo of the central part in different projections (SEM).

The formation of the device chip pattern was carried out on a single substrate. The substrate for the spin device was a square plate (10 x 10 x 0.4 mm in size) of undoped n-InSb (100), cut from an industrial polished plate with a diameter of 50 mm. The surface roughness of the substrates was 1.5-2.0 nm. Before the first photolithography stage, the substrates were cleaned of impurities, adsorbed films and oxides.

To remove visible surface contaminants such as grease stains, dust, etc. we used boiling and drying in isopropyl alcohol vapors, ultrasonic cleaning in organic solvents (acetone or N,N-dimethylformamide) and washing in deionized water. The presence of adsorbed impurities, monolayers from previous photoresist coatings, oxide films also leads to the deterioration of the sample surface. The removal of surface oxides was carried out by annealing or etching with Ar ions [5]. The most result was obtained by ultrasonic cleaning in an organic solvent with washing in deionized water and additional ion cleaning. As a result, the substrate surface was so hydrophilic that the water contact angle tends to maximum, and the photoresist contact angle tends to 0, and the semiconductor surface roughness was comparable to the thickness of the created tunnel barrier [6].

The elements of the device chip are formed using the contact photolithography method, where the source of actinic radiation is ultraviolet radiation from a mercury lamp (I-line, wave length is 365 nm). To achieve high accuracy of reproduction of the geometry of the elements we used a set of color-coated photomasks (Fe oxide), which have a low reflection coefficient of the masking coating.

In the case of contact photolithography, a sample with a deposited photoresist and a photo mask (a glass plate coated with vacuum deposition) should be in close contact with each other. In reality, however, there microgaps arise since the surface of a sample is not absolutely flat, a “border” occurs when photoresist is applied on a square substrate, etc.; all this can distort the size and shape of elements due to the divergence of the light beam. Taking into account the presence of diffraction phenomena and the effects of reflection in the photomask - photoresist - substrate system the optimal parameters of exposure and development were selected, in which the dimensions of the obtained elements corresponded to those specified on the photomask. Figure 2 shows the photo of the sample after exposure and development at the stage of formation of ferromagnetic strips taken with an optic microscope (OM). One can see that the decrease or increase in the exposure time by 1 second from the optimal one results in distortion of images with micron sizes.
The next step is the transfer of the topological layer pattern specified by the photomask to the substrate, i.e. surface treatment, uncovered resistive layer. This technological operation is carried out both liquid and "dry" methods of etching. Because of the difficulties in selecting the required liquid etchant, the method of reverse “explosive” photolithography (Lift-off process) was used, both to create a tunnel barrier and ferromagnetic contacts, and to form conductive tracks and contact pads. The inverse image transfer occurred after the active layer was sprayed onto the photoresistive mask, and further removal of unnecessary areas was combined with the operation of removing this mask. To create ferromagnetic contacts and a tunnel barrier between the semiconductor and the metal, MgO (2nm) / CoFe (80nm) / Ta (50nm) trilayer film was obtained by magnetron sputtering in one cycle without removing the substrate from the vacuum chamber. The current paths and contact pads are formed by a film of successively deposited Ni (30nm), Cu (30nm) and Ag (80nm) layers, where Ni and Cu layers are obtained by magnetron sputtering, and the Ag layer is formed by resistive evaporation. “Explosion” (swelling and dissolution of photoresist under a layer of sprayed film) was carried out in an ultrasonic bath in an organic solvent (acetone or N, N-dimethylformamide). The disadvantages of the "explosion" include the formation of film irregularities in the areas of the border of the illuminated and non-illuminated areas.

Since the spin device is a multilayer structure, it is necessary to create interlayer insulation. A polymer film of a positive photoresist of FP 9120-1 (a composite of photosensitive O-naphthoquinonediazide and phenol-formaldehyde resin) was taken as a dielectric material. The film was centrifuged onto a semiconductor plate and subsequently dubbed at a high temperature in a stepped smooth mode. Thus, cracking of the resist film was prevented, and its surface remained flat and smooth. The surface topography of photoresist films was studied by atomic force microscopy. The process of creating a spin device ended with the formation of a protective layer to insulate the surface from external influences. The photoresist film FP 9120-1 was also used as a protective coating.

An indicator of the quality of a multilayer chip is reliability. It is determined by the probability of ruptures of conducting contacts. This may be due to spraying an insulating film on a rectangular step and loss of conductivity due to a break of the sprayed film along the edge of the insulator, as well as conducting low-temperature (T = 77K) electrical measurements. The photo of rupture of a ferromagnetic contact is shown in Figure 3.

**Figure 2.** A sample of InSb in the modes of exposure and development during the formation of ferromagnetic strips: a) overexposure, b) underexposure, c) optimal exposure (OM).
Figure 3. Rupture of a ferromagnetic contact: a) upon transition from an insulating film of FP 9120-1 to an InSb substrate (SEM); b) on the isolating film FP 9120-1 when the ferromagnetic contact is switched to an electrical contact (OM).

3. Hanle effect
The developed technological process allowed creating a lateral spin devices with high efficiency of spin polarization transfer from a ferromagnetic metal into n-InSb. This is confirmed by studying the Hanle effect. The method of measuring the Hanle effect is described in detail in [3, 4].

Figure 4. Voltage $U_{H}$ generated by spin-polarized electrons in an InSb-based lateral spin devices. Injector current is 15 µA. 1 - the surface was cleaned with Ar ions for 3 min at a power of 100 W, 2 - the surface was cleared with Ar ions for 1.5 min at a power of 25 W. Experimentally measured voltage is shown with circles, solid curves are results of calculation.

Figure 4 shows the results of measurements of the voltage of the Hanle effect produced by polarized electrons at the detector in the device, when an MgO tunneling barrier was formed on the surface of a semiconductor with high and low roughness. Different roughness values were obtained with different modes of cleaning the surface of the plates with Ar ions and depended on the etching time and the power supplied to the ion etching device. One can see that the efficiency of spin injection, which is proportional to the voltage $U_{H}$, is significantly higher in a device with a smooth semiconductor surface. The experimental results are in good agreement with the theory developed in [3].

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