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Surface Hall Potentiometry to Characterize Functional Semiconductor Films

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1. Introduction

In this paper, a novel surface potentiometry is presented in order to evaluate internal electronic properties of semiconductor films. In order to fabricate semiconductor devices in the next generation, it is required to form functional semiconductor thin films with higher performances than those used today. For example, a p-n junction locus and a mobility distribution is important for MOS transistors on SOI substrate and thin film transistors, respectively. It is required to evaluate those electronic properties of semiconductor thin films locally. The Hall effect is well known as a classical method to measure the carrier type (hole or electron), the carrier concentration and the mobility of semiconductors [1]. However, the conventional Hall effect only gives average information of the sample. We suggest projecting the Hall effect induced inside a semiconductor film to the change of surface potentials, which we call "surface Hall potential". When the distribution of the surface Hall potential is visualized on the nanometer-scale, it is expected to extract the local variation of electronic properties inside the film or the film structure relating to local defects and crystallinity. In this paper, the principle of the method is introduced, and surface Hall potential measurements are demonstrated by the Kelvin method [2] with silicon wafers and an SOI wafer in order to test the proposed method.

2. Measurement principles

The basic setup is shown in Fig. 1 in which an electric field and a magnetic field is applied along the x and z direction inside the horizontal plane of the semiconductor film, respectively. Then the Hall field that balances the Lorentz force appears along the y direction, and this generates the Hall voltage (V_y) between the surface and the backside of the film.

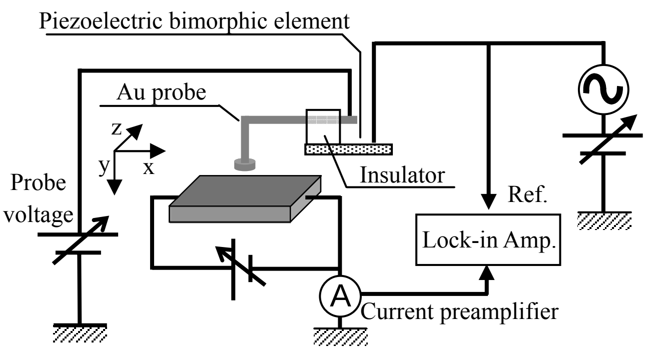

Fig.1 Schematic drawing of the electrical circuit. Along the x and z direction in the sample, an electric and a magnetic field is applied, respectively.

An approximate expression for the Hall voltage is $V_y=\pm av_xB_z$ where a, v_x, B_z is the thickness of the film, the drift velocity of the carrier and the magnitude of the magnetic field, respectively. The sign of V_y depends on the carrier type (hole or electron). We predict that the change of surface potentials by the insertion of the magnetic field is proportional to the Hall voltage between the surface and the backside of the film. Namely, measuring the surface Hall potential enables us to extract information about the carrier type and the drift velocity of the current flow. This can be a novel surface analysis to investigate structures inside semiconductor films.

3. Experimental set-up

Schematic drawing of the electrical circuit for the Kelvin method is also depicted in Fig. 1. A bimorphic vibrator was oscillated by AC voltage at the frequency of 53Hz. A reference electrode in the form of an Au round plate (1.0 mm in diameter) extending into an L-shaped wire was attached at the piezoelectric bimorphic element. The signal generated by the capacitor between the Au probe and the sample surface was fed to a current preamplifier with 10^{-8} A/V gain. The amplified signal was measured by a lock-in amplifier. External bias voltage (V_{ex}) was applied to the Au probe so that a phase change of 180° is detected in a null method by the lock-in amplifier. A sensitivity of 1 mV was achieved by this system. In order to induce the Hall effect, current is applied to the sample. In the horizontal plane of the sample, a magnetic field (0.7 T) can be applied by the transfer of a neodymium-iron-boron magnet in the direction perpendicular to the current flow. The energy level diagram in Fig. 2 shows the definition of the surface Hall potential. In Fig. 2, the sample is assumed to be a p-type Si. Figure 2(a) is a schematic depiction of electronic energy relations between the Au probe and the sample surface beneath the probe under the current flow inside the sample. The contact potential difference measured by the Kelvin method consists of two factors. The first one is the difference of work functions (φ_D) between the Au probe and the sample surface under the condition without applied current. The other one is a potential beneath the Au probe (qV_c) derived from the potential distribution to generate applied current. After the compensation point ($qV_{ex}=qV_{cpd1}=\varphi_D+qV_c$) is determined by the Kelvin method, the magnetic field is applied to the sample and the contact potential under the magnetic field (qV_{cpd2}) is measured again. The difference of the two contact potentials ($qV_{SHP}= qV_{cpd2}-qV_{cpd1}$) is the change of surface potentials by the Hall effect inside the sample, which is called the surface Hall potential. The surface Hall potential measurements were performed with two types of Si wafers ((1) p-type Si(001) (ρ= 8.5-11.5 Ω･cm) with the thickness of 625 μm, (2) n-type Si(001) (ρ= 8-20 Ω･cm) with the thickness of 625 μm) and an SOI wafer (p-type SOI layer with the thickness of 100 μm). Prior to measurements with the Kelvin method, every sample was cleaned with a mixed solution of H_2SO_4 and H_2O_2 in order to remove either organic or metal contamination. Then it was dipped into dilute HF solution in order to strip chemical oxides, and terminate the surface with H atoms.

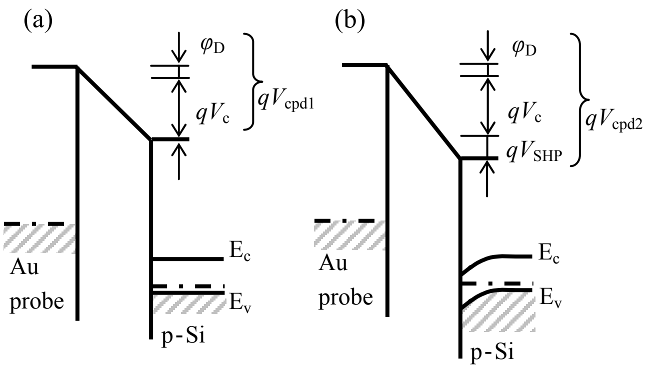

Fig.2 Schematic of the energy band diagram between the Au probe and a p-type Si sample. (a) The contact potential difference under an applied current to the Si sample (qV_{cpd1}) is composed of φ_D and qV_c. (b) By applying a magnetic field perpendicular to the applied current, the contact potential difference (qV_{cpd2}) increases because of the appearance of the surface Hall potential (qV_{SHP}). On n-type Si samples, however, the contact potential difference (qV_{cpd2}) decreases by the magnetic field, because the sign of the surface Hall potential is inverted.

4. Results

Figure 3 shows results with silicon wafers. In Fig.3, surface Hall potentials proportional to applied current are detected in both p-type and n-type wafers. And the sign of the surface Hall potential depends on the carrier type (hole or electron). Figure 4 is a result on an SOI layer. The detected surface Hall potential is proportional to the applied current again. In Figs. 3 and 4, the absolute value of the surface Hall potential for n-type Si samples is larger than that with p-type Si samples. One of the main reasons for this is that the carrier mobility of electrons is larger than that of holes in general, and the calculated Hall voltage for n-type Si samples is larger than that for p-type silicon samples. These results in Figs. 3 and 4 indicate that the Hall effect occurred in the film is reflected to the surface Hall potential. It is necessary to improve the measuring apparatus to project the Hall effect inside the film to surface Hall potentials with high sensitivity. And we are going to visualize the distribution of the surface Hall potential on the nanometer-scale by scanning probe techniques in order to elucidate local structures inside the semiconductor film including scattering centers and p-n junction loci.

5. Conclusions

A novel surface potentiometry is proposed to evaluate semiconductor films. When a magnetic field is applied perpendicular to the electric field in the horizontal plane of the film, we predict that surface potentials change by the Hall effect inside the film. This idea is demonstrated with silicon and SOI wafers by the Kelvin method.

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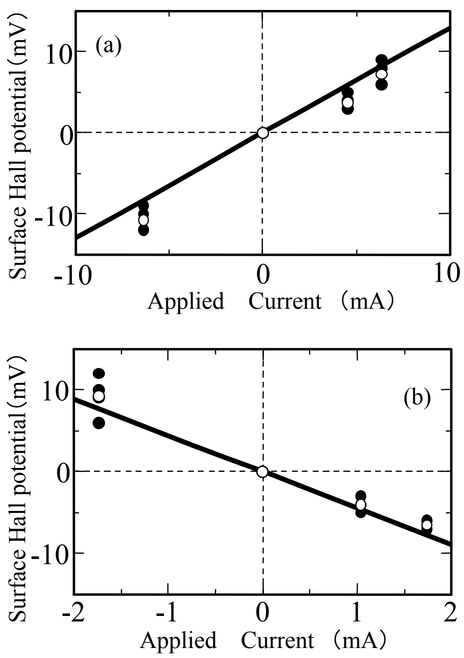

Fig.3 Results of surface Hall potential measurements on a (a) p-type and (b) n-type Si wafer, respectively. Solid circles represent measured data. Open circles represent an average among three measured data at each applied current.

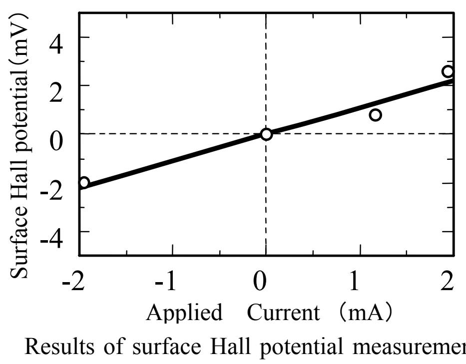

Fig. 4 Results of surface Hall potential measurements with a p-type SOI layer.