SHORT COMMUNICATION

Magnetoresistance due to the Lorentz force in silicon membrane

Chitnarong Sirisathitkul[1], Haruthai Longkullabutra[2], Praiwan Kirdtongmee[2], Said Aslam[3] and John Gregg[4]

Abstract

Sirisathitkul, C., Longkullabutra, H., Kirdtongmee, P., Aslam, S. and Gregg, J.
Magnetoresistance due to the Lorentz force in silicon membrane
Songklanakarin J. Sci. Technol., 2002, 24(2) : 305-310

The Lorentz force gives rise to helical paths of moving charged particles in a magnetic field and these, in turn, result in reduction of mean free paths and higher scattering rates. This effect may be observed from magnetoresistance in a 1-µm thick silicon membrane. With a transverse current, the electrical resistance of the p-type silicon increases by 0.4% in a 1.6-tesla magnetic field at room temperature. The magnetoresistance increases to 1% at 250K. The plot of electrical resistance versus magnetic field can be approximated as a parabola and the hole mobility may be determined as 405 cm^2/Vs at 290K and 610 cm^2/Vs at 250 K.

Key words : magnetoresistance, Lorentz force, silicon membrane

---

[1]D.Phil. (Physics), [2]B.Sc. (Physics Education), Magnet Laboratory, Walailak University, Nakhon Si Thammarat 80160, Thailand, [3]Ph.D. (Physics), Solid State Device Development Laboratory, Goddard Space Flight Centre, NASA, Washington DC 20546, USA., [4]D.Phil. (Physics), Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK.
Corresponding e-mail: schitnar@wu.ac.th
Received, 16 August 2001 Accepted, 15 January 2002

บทคัดย่อ

ชิตณรงค์ ศิริสถิตย์กุล[1] หฤทัย ล่องกุลบุตร[1] ไพรวัลย์ เกิดทองมี [1] ซาอิด อัสลาม[2] และ จอห์น เกร็ก[3]

แมกนีโตรีซิสแตนซ์เนื่องจากแรงลอเรนซ์ในซิลิกอนเมมเบรน

ว. สงขลานครินทร์ วทท. 2545 24(2) : 305-310

แรงลอเรนซ์ที่กระทำบนอนุภาคที่มีประจุซึ่งเคลื่อนที่ในสนามแม่เหล็ก ทำให้อนุภาคนั้นมีเส้นทางการเคลื่อนที่เป็นเกลียวโค้ง ซึ่งส่งผลให้อนุภาคมีวิถีอิสระเฉลี่ยลดลง และมีอัตรากระเจิงสูงขึ้น ผลที่เกิดขึ้นนี้สามารถสังเกตได้จากปรากฏการณ์ แมกนีโตรีซิสแตนซ์ ในเมมเบรนของซิลิกอนที่มีความหนา 1 ไมโครเมตร การทดลองที่ผ่านกระแสไฟฟ้าในทิศตามขวางพบว่าความต้านทานไฟฟ้าของซิลิกอนมีค่า เพิ่มขึ้น 0.4% ในสนามแม่เหล็ก ขนาด 1.6 เทสลาที่อุณหภูมิห้อง และแมกนีโตรีซิสแตนซ์เพิ่มเป็น 1% ที่ 250 เคลวิน กราฟความสัมพันธ์ระหว่างสนามแม่เหล็กกับความต้านทานไฟฟ้าสามารถประมาณได้เป็นพาราโบลาซึ่งสามารถนำไปสู่การคำนวณค่าโมบิลิตีของโฮลได้เท่ากับ 405 ซม.^{2}/โวลท์.วินาที ที่ 290 เคลวิน และ 610 ซม.^{2}/โวลท์.วินาที ที่ 250 เคลวิน

---

[1] ห้องวิจัยแม่เหล็ก มหาวิทยาลัยวลัยลักษณ์ อำเภอท่าศาลา จังหวัดนครศรีธรรมราช 80160 [2] Solid State Device Development Laboratory, Goddard Space Flight Centre, NASA, Washington DC 20546, USA., [3] Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK.

In the presence of a magnetic field with an electric field, the Lorentz force acting on charged particles may be written as $\mathbf{F} = q(\mathbf{v}x\mathbf{B})$ where q , **v**, **E**, and **B** are charge, velocity of the particles, the electric field and the magnetic field, respectively. When a semiconductor is subjected to a magnetic field, holes and electrons follow helical paths and their mean free paths are, therefore, reduced. This mechanism may be observed from a magnetoresistance measurement in which the resistivity of semiconductor increases without saturation in externally applied magnetic field. The characteristics of magnetoresistance differ from those of the Hall effect. While the Hall voltage is field-odd and proportional to B, the magnetoresistance is a function of B^2 and field-even (Lorrain *et al.*, 1988). Both phenomena have been extensively studied because of their applications in magnetic sensing and recording. If ρ_0 represents resistivity in zero magnetic field and $\Delta\rho$ is the change of resistivity in applied magnetic field, the magnitude of magnetoresistance ($\Delta\rho/\rho_0$) may be written as $\Delta\rho/\rho_0 = M_tB^2$ where M_t is a transverse magnetoresistance coefficient.

In this paper, magnetoresistance of a sample composed of a silicon membrane was studied and the carrier mobility (μ) was deduced from the experimental results.

Materials and Methods

As shown in Figure 1, the sample is a p-type silicon membrane sandwiched by two nickel layers. The silicon resistivity is 20-30 Ωcm and this corresponds to the impurity (boron) concentration of 4×10^{14}-7×10^{14} cm^{-3}. From the sample fabrication at NASA Goddard space flight centre, the sample was grown on a <100> p-type SOI (silicon on insulator) wafer. Photolithography was performed in order to define a 10-µm^2 rectangular pattern on the wafer. This area was further developed into a silicon membrane by selective etching and thinning. The selective etching was performed to isolate the membrane from other silicon areas. To reduce the thickness of the membrane, the back of the wafer was etched by KOH leaving a pit with only 1-µm thick silicon membrane at the bottom. Subsequently, 200-nm nickel films and 500-nm gold contacts were deposited by sputtering. On the other side of the wafer, nickel and gold contacts were selectively deposited. After the fabrication, the sample was sliced from the wafer. At

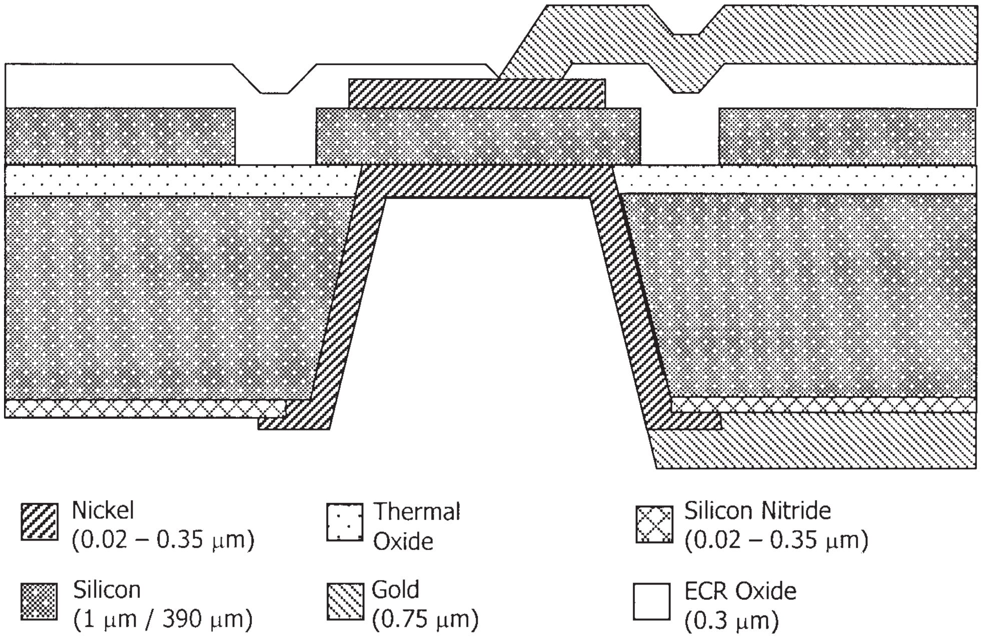

Figure 1. Geometry of the sample. The thickness of silicon is 1 μm for the membrane and 390 μm for the bulk silicon. The oxide isolates the membrane from the bulk silicon. Nickel and gold films act as electrical contacts to the measurement circuits.

Clarendon Laboratory, University of Oxford, the sample was mounted on a sample holder with ultrasonic wire bonding to the gold contacts and connected to the end of a measurement probe. The probe was inserted in a cryostat between electromagnet's pole faces. Current-voltage characteristics and resistance measurements were performed from room temperature down to 100 K. In the magnetoresistance measurements, the two-point technique was performed using a 0.35 mA constant transverse current (perpendicular to the membrane's plane and magnetic field).

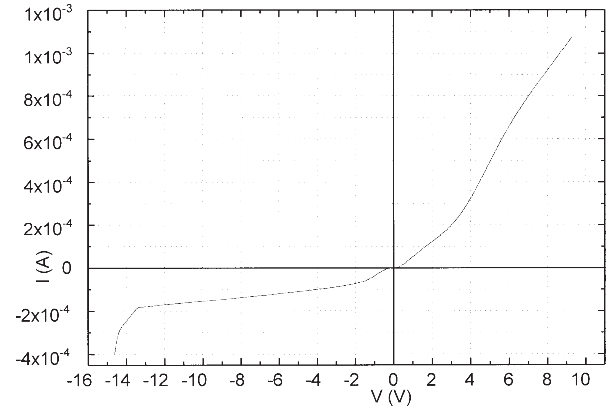

Figure 2. Current-voltage characteristics of the sample at 290 K.

Results and Discussion

Current-voltage characteristics at 290 K of the sample are shown in Figure 2. Nickel/silicon junctions give rise to the Schottky diode behaviours. The rectification is due to asymmetry between two Schottky barriers and substantial leakage current through one of the nickel layers. As seen in Figure 3, the resistance of the sample increases exponentially with the decreasing temperature. This reflects the conduction properties of silicon as a function of temperature. According to the magnetoresistance measurements at 290 K, the silicon membrane exhibits 0.4% resistance increase in a 1.6-tesla magnetic field without saturation. The

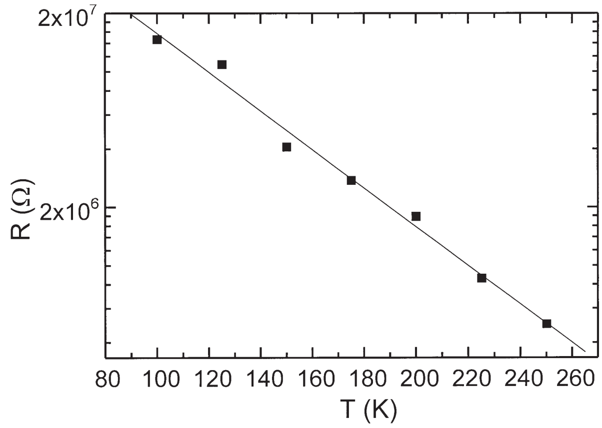

Figure 3. Differential resistance (0.5 µA test current) of the sample between 100 and 260K.

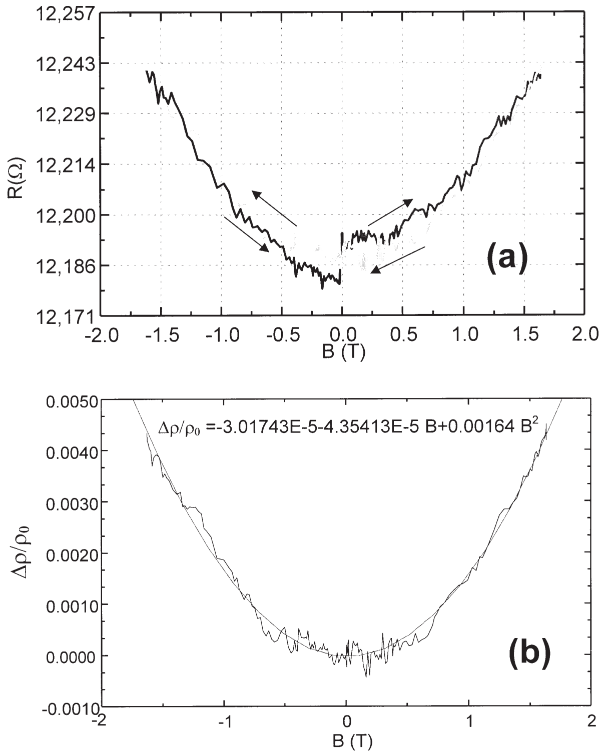

Figure 4. (a) Magnetoresistance curve at 290K. The arrows indicate the sequence of the magnetic field sweep.
(b) Curve fitting of the magnetoresistance characteristics.

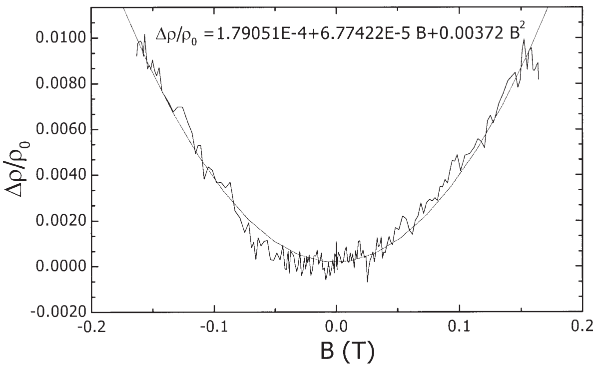

Figure 5. Magnetoresistance and curve fitting at 250K.

magnetoresistance increases to 1% at 250K. Magnetoresistance below 250K is not observable because it is overshadowed by signal fluctuations. The magnetoresistance curves at 290 and 250 K are shown in Figures 4 and 5, respectively. They can be approximated as parabola curves. This is attributable to the effect of the Lorentz force on the trajectories of conduction holes in the silicon.

Consider a silicon membrane diagram in Figure 6. An externally applied electric field and a magnetic field are in the X- and Z-axis, respectively. Owing to the Hall effect, charge carriers are accumulated on both sides of the silicon membrane and this gives rise to an electric field perpendicular to the current flow and the magnetic field (in the Y-axis). The Lorentz force acting on conduction holes may be written as:

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v}\mathrm{x}\mathbf{B}) \qquad (1)$$

Since $$\mathbf{F}/q = \mathbf{v}/\mu \qquad (2)$$

Equation (1) can be written as:

$$\mathbf{v} = \mu\,(\mathbf{E} + \mathbf{v}\mathrm{x}\mathbf{B}) \qquad (3)$$

Components of the velocity in each axis are defined as:

$$v_x = \mu\,(E_x + v_y B) \qquad (4)$$

$$v_y = \mu\,(E_y - v_x B) \qquad (5)$$

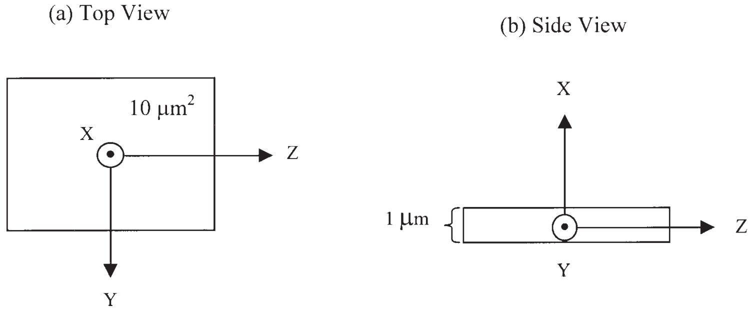

Figure 6. Diagram showing axis assignment for the silicon membrane.

$$v_z = 0 \quad (6)$$

where E_x is an electric field in the direction of current flow. E_y is due to the Hall effect.

Substituting (5) into (4), v_x becomes :

$$v_x = \mu\,[E_x + \mu\,(E_y - v_x B)B]$$

$$(1+\mu^2B^2)v_x = \mu\,(E_x + \mu\,BE_y)$$

$$v_x = \mu\,(E_x + \mu\,BE_y)\,/\,(1+\mu^2B^2) \quad (7)$$

Current density is defined as:

$$J_x = nqv_x \quad (8)$$

Substituting (7) into (8), the current density in the X-axis becomes:

$$J_x = nq\mu\,(E_x + \mu\,BE_y)\,/\,(1+\mu^2B^2) \quad (9)$$

Nickel films are deposited on both sides of the silicon membrane and the charge carriers are able to flow across the Schottky barriers to nickel. Consequently, E_y is approximately zero and equation (9) is reduced to:

$$J_x = nq\mu E_x\,/\,(1+\mu^2B^2) \quad (10)$$

From a definition:

$$J_x = (1/\rho)E_x \quad (11)$$

Comparing equation (10) and (11), the resistivity can be written as:

$$\rho = (1+\mu^2B^2)/\,nq\mu \quad (12)$$

The resistivity in zero magnetic field (ρ_0) and the change in resistivity ($\Delta\rho$) are:

$$\rho_0 = 1/\,nq\mu \quad (13)$$

$$\Delta\rho = \rho - \rho_0 = \mu^2B^2/\,nq\mu \quad (14)$$

The magnetoresistance ($\Delta\rho/\rho_0$) is then equal to:

$$\Delta\rho/\rho_0 = [\mu^2B^2/\,nq\mu]\,/\,[1/\,nq\mu] = \mu^2B^2 \quad (15)$$

Hence, the magnetoresistance can be fitted to a second order polynomial function of magnetic field. Taking Figure 4b as an example, the curve may be represented by the equation: $\Delta\rho/\rho_0 = 0.00164B^2-0.0000435B-0.0000302$. The negligible second term is due to the Hall effect. The first term corresponds to the magnetoresistance and the transverse magnetoresistance coefficient ($M_t = \mu^2$) is 0.00164. As a result, the mobility of the hole conduction in p-type silicon membrane at 290 K may be determined as 405 cm^2/Vs. As reported by Sze (Sze, 1981), the drift mobility of holes in silicon with impurity concentration of 4×10^{14} - 7×10^{14} cm^{-3} at 300K is about 400 cm^2/Vs and this is in good agreement with the experiment. In a similar fashion, the mobility at 250 K is obtained as 610 cm^2/Vs. The mobility increases with the decreasing temperature as predicted. The drift mobility derived from this magnetoresistance experiment should be distinguished from the Hall mobility (μ_H) obtained from the Hall effect. The degree of difference between the Hall mobility and the drift mobility depends on how much acoustic phonon scattering and ionised impurity scattering are involved in the process.

Conclusion

Magnetoresistance due to the Lorentz force in a p-type silicon membrane is observed. The magnitude of effect is about 0.4% at room temperature and increases to 1% at 250K. Magnetoresistance curves were fitted as parabola and results follow an equation $\Delta\rho/\rho = \mu^2B^2$. Hole mobility in p-type silicon was deduced as 405 cm^2/Vs at 290 K and 610 cm^2/Vs at 250 K.

References

Lorrain, P., Corson, D.R. and Lorrain, F. 1988. Electromagnetic fields and waves, 3rd ed., W.H. Freeman and company, New York.

Sze, S.M. 1981. Physics of Semiconductor Devices, 2nd ed., John Wiley and Sons, New York.