Effect of Substrate Thickness on Horizontal Magnetoresistance

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Abstract. This paper presents the effect of substrate thickness on horizontal magnetoresistance that detects the horizontal magnetic field perpendicular to bulk cross section area. The substrate thickness (T) concerns directly to the current density distribution and the effective depth (t) of current path corresponding to cross section area of current. The horizontal magnetoresistance depends on current distribution which concerns with substrate concentration, length, width and thickness of resistor. It changes by the effective depth of current path change by the unbalance between Lorentz’s force and Hall electrical force in vertical direction. From this study, the sensitivity of device increases with the thickness of substrate up to critical substrate thickness and still constant for thickness greater than this critical value. The current distribution is limited when substrate thickness less than a critical value and fully distributes when the thickness is greater than this value. At the same constant current, the longer length of resistor shows the lower current density which needs the longer effective depth of current which causes the critical substrate thickness to be increased accordingly.

1. Introduction
The geometry magnetoresistance is the Hall effect current mode for non-magnetic material such as semiconductor [1-3]. It uses Lorentz’s force induced from vertical magnetic field deflect currents to make the current path longer, resulting in higher resistances. It has to design a specific geometry to make induced Lorentz’s force greater than induced Hall electrical force for current deflection [4]. The magnetoresistance also occurs in horizontal magnetic field [5]. It occurs as a latent phenomenon in the operation of the device, for example, 5-contact vertical Hall device for detecting horizontal magnetic fields [6]. In addition to the Hall effect caused by horizontal magnetic fields, there is also a horizontal magnetoresistance phenomenon [5, 6]. The mechanism of this effect is not as clear as vertical magnetoresistance because of the asymmetry current path in vertical direction [7]. The mechanism is the unbalance between Lorentz’s force and Hall electrical force in vertical with asymmetry current paths of planar resistor [8]. The horizontal magnetoresistance is a geometry magnetoresistance that depends on geometry of device in planar. The thickness of bulk is an important variable and directly related to this phenomenon other than the geometric of device [9, 10]. In this study, the effect of thickness on horizontal is studied by TCAD method [11, 12]. The simulation helps to see the distribution of current density from the magnetic field, which leads to more understanding.
2. Mechanism of horizontal magnetoresistance

Introduction

The mechanism of horizontal magnetoresistance can be explained as in figure 1. The horizontal magnetoresistance will occur when the substrate concentration is low [13]. The current is biased by constant current from cc1 to cc2 and electron in n-type substrate flow from cc2 to cc1 in bulk with the effective depth $t$ as shown in figure 1 (b). When the magnetic field is applied in $-y$ direction as shown in figure 1 (a), the induced Lorentz’s force $F_L$ acts upon the electron in $-z$ direction. The Hall electric field is induced in the opposite $z$ direction. In this case, the force from Hall electrical field $F_H$ is less than Lorentz’s force ($F_L > F_H$) causes the electron current paths are longer deep into bulk in $-z$ direction and increases resistance. On the other hand, the Lorentz’s force is induced in $z$ direction when the magnetic field is applied in $y$ direction. In this case, the Hall electrical force is induced into bulk in $-z$ direction and less than Lorentz’s force ($F_H < F_L$) and electron current paths are shorter up to surface and the resistance is reduced. The reason of the unbalance of two forces because the current paths in cross section area is asymmetry as in the case of planar. It can be explained as in the equation below

$$R = \rho \times \frac{L}{A} = \left( \frac{\rho}{\mu} \right) \left( \frac{L}{W} \right)$$

where $R$ is resistance, $\rho$ is resistivity, $L$ is length of resister and $A$ is cross section area of current. The cross section $A$ can be rewritten into term of width ($W$) and thickness of current ($t$) which is appropriate average value that represent of depth corresponding to the cross section area $A$ and resistance change $\Delta R$ when applied magnetic field is

$$\Delta R = \rho \left( \frac{L}{W} \right) \times \frac{I}{\Delta t}$$

where $\Delta t$ is the average current depth change from magnetic field. The average current depth $t$ depends on the current distribution profile which is concern with the thickness of substrate $T$.

![Figure 1. Cross section of horizontal magnetoresistance at low concentration substrate.](image)

3. Device structure and TCAD

The device and simulation structure is shown in figure 2. The dimensions are width $W_d$, length $L_d$, thickness $T$, contact width $W$ and length between contact $L$. The substrate is N-type with the low concentration $10^{14}$ cm$^{-3}$. The thickness is varied at 5, 10, 15, 20, 30 and 70 $\mu$m. The contact width is 5 $\mu$m and length $L$ is varied at 5, 10 and 25 $\mu$m. The biased current is 1 mA. The tool for this study is by simulation by Synopsis TCAD Sentaurus program. The important semiconductor equations and magnetic model are completely in this program [14].
Figure 2. Resistor structure (a) Device dimensions (b) Simulation structure.

4. Experiments and Discussion

The parameters that we study are substrate thickness $T$ of the length between contacts $L$. The magnetic field $B$ is applied perpendicular to cross section area in parallel direction. The horizontal magnetic responses that we study are the resistance change $(\Delta R)$ and percentage of resistance change (%$MR$). The definition of them are written as

$$%MR = \% \frac{\Delta R}{R} = \frac{R(B) - R(0)}{R(0)} \times 100$$

(3)

where $R(B)$ is applied magnetic field resistance and $R(0)$ is non-applied magnetic field resistance. The $\Delta R$ and %$MR$ of magnetoresistance are shown in figure 3. The resistance $L=5$, 10 and 25 $\mu$m, biased current 1 mA and magnetic field 0 – 0.5 T at substrate thickness 5, 10, 15, 20, 30 and 70 $\mu$m are in figure 3(a), (b) and (c), respectively. The sensitivity ($S$) or slope of graph, the resistance change $\Delta R$ and %$MR$ increase with substrate thickness up to a critical substrate thickness value and still constant when substrate thickness is greater than this value. The critical thickness of resistor $L = 5$, 10 and 25 $\mu$m are approximately 5, 15 and 30 $\mu$m, respectively. All of them show linearly dependence. The non-magnetic field resistance $R(0)$ reduces with the substrate thickness down to the saturation value. Table 1 summarizes $R(0)$, $\Delta R$, %$MR$ and $S$ of all devices. The %$MR$ of longer resistor at same constant current is greater than the shorter resistance. The %$MR$ is less than 1 % but if it is considered the resistance value, it is changed up to several kilo ohms for $L = 25 \mu$m at 0.5 T by the substrate thickness more than 30 $\mu$m.

Figure 4 and 5 show the current distributions of magnetoresistance of the shortest resistor $L = 5$, and longest resistor in this study $L = 25 \mu$m at substrate thickness 5, 10 and 30 $\mu$m, respectively. The short resistor in figure 4, the current density is high between the contacts and the long resistor in figure 5, the current density is lower than the short one. The current density depth of short resistor in figure 4 is shallow than the long one in figure 5. It can be said that the current density is reduced according to the length $L$ of resistor for same constant current. At substrate thickness 5 $\mu$m, it can be observed that the depth of current is limited by the substrate thickness both of short and longer resistor as shown in figure 4 (a) and (5). At substrate thickness 10 $\mu$m, the depth of current of shorter resistor in figure 4 (b) is mostly covered by the thickness of substrate than in the case of longer resistance $L = 25 \mu$m. It can be observed that in figure 5 (b) the depth of current is almost covered by substrate thickness but is not complete. At the substrate depth 30 $\mu$m in figure 4 (c) and 5 (c), the shorter resistor current depth is
Figure 3. Magnetoresistance and $% \text{MR}$ responses of resistor.

Table 1. $R$, $\Delta R$, $% \text{MR}$, $S$ of magnetoresistance

| $T$ ($\mu$m) | $L = 5 \mu$m | $L = 10 \mu$m | $L = 25 \mu$m |
|-------------|--------------|--------------|--------------|
|              | $R$ ($k\Omega$) | $\Delta R$ ($\Omega$) | $% \text{MR}$ (%) | $S$ ($k\Omega$/AT) | $R$ ($k\Omega$) | $\Delta R$ ($\Omega$) | $% \text{MR}$ (%) | $S$ ($k\Omega$/AT) | $R$ ($k\Omega$) | $\Delta R$ ($\Omega$) | $% \text{MR}$ (%) | $S$ ($k\Omega$/AT) |
| 5           | 81.3          | 88            | 0.10        | 17,723        | 220          | 147            | 0.06        | 29,551        | 994          | 254            | 0.02        | 50.908        |
| 10          | 75.5          | 221           | 0.29        | 44,368        | 180          | 419            | 0.23        | 83,900        | 637          | 782            | 0.12        | 156.58        |
| 15          | 74.8          | 303           | 0.40        | 60,787        | 173          | 645            | 0.37        | 129,07        | 543          | 1286           | 0.23        | 257.26        |
| 20          | 74.1          | 313           | 0.42        | 62,623        | 170          | 816            | 0.47        | 163,28        | 506          | 1787           | 0.35        | 357.50        |
| 30          | 74.3          | 307           | 0.41        | 61,493        | 169          | 846            | 0.49        | 169,26        | 478          | 2483           | 0.51        | 496.64        |
| 70          | 74.2          | 308           | 0.41        | 61,729        | 168          | 831            | 0.49        | 166,37        | 459          | 2542           | 0.55        | 508.57        |
Figure 4. Current density distribution of resistor $L = 5 \, \mu m$.

As the results mentioned before, the model for discussion is shown in figure 6. The resistor is biased by constant current will create the current paths between contacts. The current depth $t$ in figure 6 is the depth that corresponds to the biased current value. The current depth can be written as in the term of resistance in table 1

$$R = \frac{\rho L}{A} = \frac{\rho L}{W_d t}$$  \hspace{1cm} (4)

$$t = \frac{\rho L}{W_d R}$$  \hspace{1cm} (5)

where $R$ is the minimum saturation resistance, $\rho$ is resistivity and $W_d$ is the width of current. The cross section area $A$ is defined as the product of width $W_d$ and depth $t$. The current density is reduced when the length $L$ of device increases. The current density $J$ can be written as

$$I = \frac{J}{A} = \frac{J}{W_d t}$$  \hspace{1cm} (6)

The lower current density $J$, the longer current depth $t$ is corresponding to constant current $I$. The resistance of longer substrate thickness will give the lower resistance because the cross section area is increased from the current depth. The substrate thickness $T$ that shorter than current depth $t$ will limit the sensitivity of magnetoresistance. The carrier current distribution is limit by substrate thickness. The substrate thickness that cover the depth of current $t$, the carrier current can distribute completely
in bulk that the sensitivity is maximum and will be saturated for the substrate thickness long over the current depth \( t \).

![Image of current density distribution](image1)

(a) \( T = 5 \ \mu m \)

![Image of current density distribution](image2)

(b) \( T = 10 \ \mu m \)

![Image of current density distribution](image3)

(c) \( T = 30 \ \mu m \)

**Figure 5.** Current density distribution of resistor \( L = 25 \ \mu m \).

![Model of current depth](image4)

**Figure 6.** Model of current depth of horizontal magnetoresistance.
5. Conclusion
The substrate thickness affects to horizontal magnetoresistance. The depth of current is the depth that represent to the cross section area corresponding to current. The substrate thickness shorter than current depth will limit current distribution, the conductance and sensitivity. The longer substrate thickness will increase current distribution, conductance, sensitivity and % $MR$. The substrate thickness that longer than current depth will allow the current distribution completely and the resistance, sensitivity and % $MR$ are saturated. The longer resistor at the same current will reduced the current density so the depth of current will increase to get the same constant current. The effect of substrate thickness should be considered for operation with horizontal magnetoresistance.

6. References
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