InSb films for magnetic sensors

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Abstract

InSb films are prepared by a source-temperature-programmed evaporation method and hot-wire recrystallization method for Hall elements and magnetoresistance (MR) elements, respectively, to reduce imperfections of the crystal structure, and their crystalline and electrical properties are studied. An optimum source-temperature programme is investigated and the films thus prepared are used for Hall elements. An X-ray analysis of the film shows a high degree of stoichiometry. Magnetically sensitive InSb films have been prepared by hot-wire recrystallization. A room-temperature MR value of $\Delta R/R_0 = 155\%$ was obtained at 1 T with a length to width ratio $(L/W) = 0.4$. Samples have been prepared by sequential deposition of In, InSb, and SiO onto unheated mica substrates.

1. Introduction

InSb has attracted much attention and has been intensively studied for its extremely high electron mobility at room temperature. Therefore InSb is the material best suited for galvanomagnetic applications, such as Hall elements and magnetoresistance (MR) elements. The sensitivity of a Hall element is inversely proportional to its thickness. However, fabrication of very thin Hall elements from bulk crystal by mechanical or chemical techniques is rather difficult. An alternative method for utilization of bulk crystal is the use of the thin-film technique, provided that the film retains the desirable electrical characteristics of the bulk material.

2. Hall elements

InSb films have been prepared by a vacuum evaporation method. However, the electrical properties of thin films prepared by this method are usually inferior to those of single-crystal bulk because of imperfections in the crystal structure and deviation from stoichiometry, so a number of evaporation experiments were undertaken in order to obtain high-electron-mobility InSb films, in which the source temperature was controlled according to prescribed source-temperature patterns.

After repeating a number of such evaporation experiments, an optimum temperature pattern was found. The substrate temperature was maintained at 455 °C throughout the entire period of the deposition process. X-ray analysis was done on samples thus prepared and the results show that the evaporated film thus obtained has a high degree of stoichiometry.

The substrate temperature inevitably influences the electrical properties of the films, which may be characterized by the electron mobility $\mu_n$ and concentration $n$. The dependence of $\mu_n$ and $n$ on the substrate temperature was measured by the Hall effect and the results are shown in Fig. 1. The highest electron mobility of 61 000 cm$^2$/V s at room temperature was obtained at a substrate temperature $T_s = 455$ °C, as shown in Fig. 1. The electron concentration corresponding to this substrate temperature was $1.6 \times 10^{15}$ cm$^{-3}$ at room temperature. It is then concluded that 455 °C is the optimum substrate temperature for the source-temperature-programmed evaporation method for InSb films.

The mobility and carrier concentration of the films also depend on the thickness. The mobility decreases as the thickness increases.

![Fig 1: Electron mobility $\mu_n$ and concentration $n$ of the evaporated InSb films at room temperature vs substrate temperature $T_s$](image-url)
as the thickness of the film decreases below 0.8 µm, the mobility is approximately constant, regardless of the film thickness. Previous publications [1, 2] show a similar break point on the mobility-thickness curve at about 3.5–4.0 µm for films prepared by other evaporation methods. This can be interpreted as an indication that the films prepared by the present method have fewer imperfections.

The magnetoresistive effect of this film was measured and the results are plotted as a function of magnetic flux density $B$ as shown in Fig. 2. A deviation from linearity in the high-magnetic-field region will appear if the film has non-uniformity [3] or a gradient [4] of the carrier concentration. However, since the plot in Fig. 2 is linear in the high-field region up to 1 T, it is believed that the films prepared by the present method have a good homogeneity.

### 3. Magnetoresistance elements

#### 3.1 Preparation of films

Semiconductor magnetoresistance (MR) elements, especially InSb films, have begun to be used widely. MR elements are superior to Hall elements because the former are two-terminal devices. For Hall elements, it is necessary to compensate the residual misalignment voltage between the Hall electrodes at zero magnetic field. As a result, the MR elements are used for numerous industrial applications, such as MR sensors to control motor speed, to sort out banknotes, to sense position or displacement, etc.

A large MR value is obtained by increasing the electron mobility ($\mu$) and decreasing the length-to-width ratio ($L/W$) of the element. A simple hot-wire method was used in the present work. This is one of the semiconductor-on-insulator (SOI) techniques.

Prior to the zone-melting process, InSb films were covered with an SiO layer to prevent Sb reevaporation. The melting point of SiO is higher than that of In$_2$O$_3$. Accordingly, an SiO protective layer was used in the present work.

The preparation procedure consists of sequential deposition of In, InSb, and SiO onto unheated mica substrates [5, 6]. They were deposited in a vacuum of $10^{-3}$ Pa from sources of 99.999% pure materials. Figure 3 shows a schematic illustration of the hot-wire recrystallization system. The typical thicknesses of the In, In + Sb, and SiO layers are 0.6, 5.0, and 0.7 µm, respectively.

The In layer first deposited provides superior adhesion of these layers to the mica substrates. The zone process melts the In layer first deposited and the In + Sb layers and accordingly InSb crystallites and excess In precipitates are prepared. In these films, the In precipitates serve as electrodes for shorting the Hall field. The dissociation of InSb occurred during the evaporation process because Sb has a higher vapour pressure than In at the same temperature. Since Sb molecules were evaporated first, these films have the structure of a double In layer, with intermediate Sb and final SiO layers as shown in Fig. 3. The SiO layer deposited last serves to prevent reevaporation of Sb molecules from the molten region during the zone-melting process.

After the zone-melting process, MR elements were fabricated as follows: The film side was covered with epoxy resin. After the epoxy resin became hard, all the mica substrates were peeled off to measure the characteristics. Silver paste was used for the electrodes.

The zone-melting process was performed in a vacuum of about 0.1 Pa with a zone-transfer speed of 10 µm/s. The films were supported on a movable holder. No difference was found between the characteristics of the films prepared under an Ar atmosphere or in vacuum. A nichrome wire and a SiC rod were used as the zone heater and the substrate heater, respectively. The mica side of the sample was placed toward the nichrome wire. A distance between the wire and mica substrate of about 1 mm was chosen to keep the temperature gradient as large as possible across the solid-liquid interface. The substrate temperature was 420 °C.

#### 3.2 Electrical properties of films

Figure 4 shows a typical value of the MR, $\Delta R/R_0$, the fractional change in the zero-field resistance $R_0$, is

![Fig. 2 Magnetoresistive effect of a sample film as a function of magnetic flux density $B$](image)

![Fig. 3 Schematic illustration of the hot-wire recrystallization system](image)
plotted as a function of the applied magnetic field \( B \) A \( \Delta R/R_0 \) of 155\% at 1 T, \( l/w = 0.4 \) at room temperature, was obtained after one zone pass. The dotted line represents the MR value before the zone-melting process and no MR effect was observed. Excess In is precipitated parallel to the zone-pass direction, since InSb grain growth propagates roughly parallel to the direction of the molten-zone motion. The perpendicular MR \( \Delta R/R_0 \parallel \) and parallel MR \( \Delta R/R_0 \perp \) denote that the dc current flowing in the sample is perpendicular and parallel to the orientation of these In precipitates, respectively. The perpendicular MR is larger than the parallel MR since these In precipitates short the Hall field. A ratio \( \Delta R/R_0 \parallel /\Delta R/R_0 \perp \) (the transverse MR anisotropy) of 2.4 was obtained.

The proposed crystal-growth mechanism is that dendritic films showing the (111) plane preferentially begin to grow from the liquid phase parallel to the SiO layer because of the temperature gradient. Then In molecules near the SiO layer combine with Sb molecules and InSb crystallites begin to grow. As they grow, excess In is pushed out to the mica side. When all the Sb molecules are consumed, the growth of InSb crystallites stops. Excess In molecules are solidified on the surface of the InSb crystallites or solidified as an In matrix between the InSb crystallites.

The largest MR value is obtained when the In precipitates are highly oriented. A high temperature increases the crystallinity of the InSb areas by preventing the reevaporation of Sb.

### 3.3 Magnetoresistive sensors

MR sensors are fabricated by the method described above.

A multi-pattern mask was adopted and each pattern was as shown in Fig. 5. For high-temperature use, glass substrates were adopted.

In order to obtain films having good electrical and crystalline properties as MR sensors, the heaters were located in the cooling chamber, the temperature profile of the zone apparatus is shown in Fig. 6.

The zone-melting process was performed in a vacuum of about \( 10^{-4} \) Pa with a zone-transfer speed of 10–20 \( \mu \)m/s.

Figure 7 shows the zone-pass dependence of electron mobility of the films at room temperature, the monitoring temperature of the zone was 510 °C.

A protective layer about 1 \( \mu \)m thick was deposited on the surface of films by high-frequency sputtering of SiO \(_x\) (Corning 7059). The largest MR values of the sensors are 100–150%/T at room temperature with a length to width ratio \( l/w = 18 \).

This value is affected by the slight In precipitates present in the films.

The temperature coefficient of the MR value is shown in Fig. 8.

### 4. Conclusions

InSb + In films were prepared on an SiO layer by hot-wire recrystallization. Samples were prepared by
The temperature coefficient of the MR value sequential deposition of In, InSb, and SiO onto unheated mica substrates.

After only one zone pass, a room temperature MR value of $\Delta R/R_0 = 155\%/{^\circ}C$ was obtained at 1 T with a length to width ratio $l/w = 0.4$.

The crystallinity of the InSb films is increased when the zone melting is processed at high temperature with a slightly In-rich condition.

In order to fabricate MR sensors for high-temperature use, InSb films including very slight In precipitates were prepared on the glass substrates by the micro-zone-melting method.

It is expected that improved MR elements could be prepared by searching for the optimum conditions of the micro-zone-melting process. The crystallinity would be increased by heating the sample with laser light. The study of such sensors is now in progress.

References

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