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Ultra-high carrier mobility InSb film by rapid thermal annealing on glass substrate

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InSb films were deposited on both mica and glass substrates using thermal evaporation and subjected to FA or RTA. Crystallinity, composition and electrical properties were investigated. High Hall electron mobility as high as 25,000 $cm^2/(Vs)$ was obtained with the capped InSb film by keeping the In:Sb ratio after RTA at 520°C for 30 sec or more without adopting epitaxial growth on glass. [http://dx.doi.org/10.1063/1.4967287]

I. INTRODUCTION

Indium Antimonide (InSb) is widely used in magnetic field sensors, thermal imaging cameras and infrared detectors due to its high carrier mobility.[1–6] It has led to the evolution not only in small Hall components used in video cassette recorders (VCR), optical drives but also household electrical appliance and car industry.[7] Furthermore, InSb has high expectation in high resolution radiation detectors.[8] InSb thin films can be fabricated with many preparation methods.[9–12] Generally, InSb layer with high carrier mobility is obtained by epitaxial growth on single-crystal substrate using expensive process such as molecular beam epitaxy (MBE).[13] On the other hand, fabricating InSb film on glass substrate has high potential from the perspective of low-cost process and functional applications.

Conventionally, in the Hall device fabrication process, InSb film deposited on mica substrate is thermally annealed to crystallize. Then, the poly-crystallized InSb film is transferred to ferrite substrate. The used mica substrate is discarded. Furthermore, remaining mica on InSb, weak heat resistance of the adhesive between ferrite substrate and the InSb are the issues of this transferring process. Hence, sheet mica is a natural material and its high commercial demand, fabrication on mica substrate is becoming expensive. In this case, glass substrate is a preferable candidate.

In case of forming InSb film on a glass substrate by thermal evaporation, ultra-high mobility TFT circuit equipped with sensitive magnetic element cannot be obtained as the electron mobility is small compared to the case of depositing on conventional mica substrate. Previously, various studies have been done on annealing effect of InSb.[14–16] On glass, heat treating using furnace annealing (FA), rapid thermal annealing (RTA) or blue laser diode annealing (BLDA)[17] after forming InSb film using thermal evaporation method, the enhancement of the crystallinity of the InSb film and high carrier mobility can be expected.

By forming this high-quality film on glass substrate, low-cost, high heat resistance, high productive sensitive magnetic element equipped with TFTs of ultra-high mobility is expected to be realized. In addition, development of the TFT equipped sensitive magnetic element process on glass and ultra-high-speed Hall IC technology can be expected.

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In this research, InSb films were deposited on both mica and glass substrates using thermal evaporation and subjected to FA or RTA. Crystallinity, composition and electrical properties of the films were investigated.

II. EXPERIMENTAL AND DISCUSSION

Pre-annealed InSb films of 1 μm thickness were deposited on glass and on mica substrates using vacuum evaporation method. InSb films were annealed using FA or RTA in order to poly-crystallize. Sheet resistance of each sample was measured using 4-point probes method. In the range of 200 nm to 900 nm wavelength, spectral transmittance was measured before and after annealing to evaluate the crystallinity of InSb films. Au electrodes were deposited on InSb film using vacuum evaporation for Hall carrier mobility measurement. Distance among each electrode was 9 mm. Hall effect measurement was conducted under flux density of 0.31 T and a current of 1 μA.

A. Furnace annealing

InSb on mica and on glass substrates were annealed at 400, 500 or 600°C for 1h using FA at N_2 gas ambient. Transmission electron microscopy (TEM) was performed to observe the grain structure. Crystallinity of the annealed samples were evaluated using spectral transmittance. Sheet resistance was measured and Hall effect measurement was also conducted.

1. Crystallinity evaluation by TEM

Fig. 1 shows TEM images of the InSb films on mica and glass substrates after FA at 500°C for 1 h. As a result of FA, InSb film has been polycrystallized. Grains ranging from 50 nm to 100 nm in diameter were formed for the InSb film on mica as shown in Fig. 1 (a). Compared to InSb on mica substrate, grain size of InSb on glass substrate after FA was not so uniform.

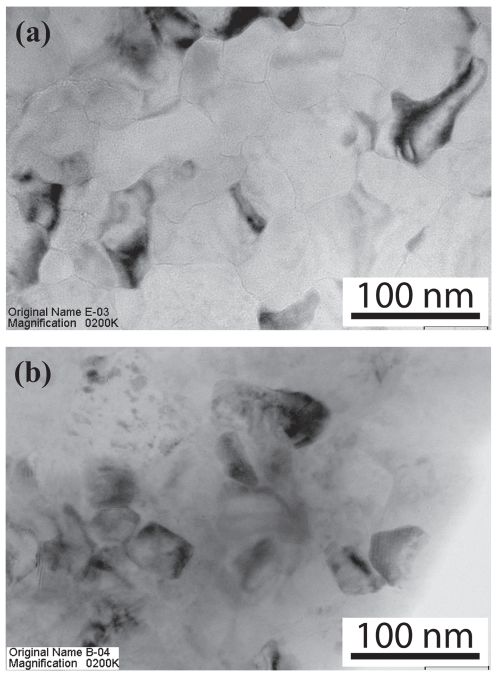

FIG. 1. TEM images of the InSb films on (a) mica and (b) glass substrates after FA.

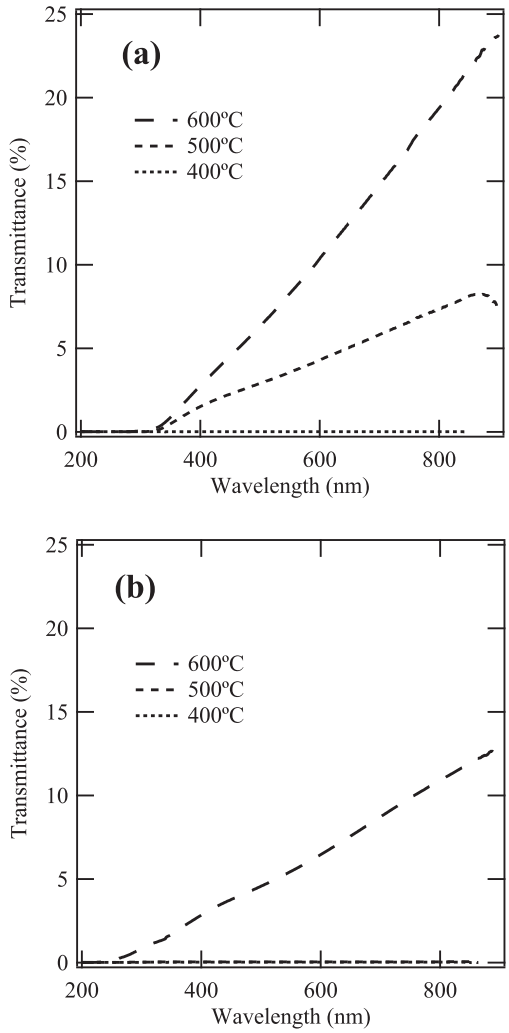

FIG. 2. Transmittance of 1 μm thick InSb films on (a) mica and (b) glass substrates after FA.

2. Crystallinity evaluation by spectral transmittance

Fig. 2 shows the optical transmittance results of InSb on mica and on glass after FA for 1 hour. Trend of increasing the optical transmittance was seen with the increase of thermal annealing temperature. Increase in the optical transmission was seen with the InSb on glass heat-treated at 600°C and InSb on mica heat-treated at 500°C. InSb is not transparent for the wavelengths between 200 nm to 900 nm before annealing. It is considered that optical transmittance of InSb film has been improved due to the increase of crystallinity after annealing. Compared to InSb on glass sample, significant difference of increase in the optical transmittance was observed with InSb on mica substrate.

3. Sheet resistance measurement

A tendency that dependence of the sheet resistance on annealing temperature after FA is shown in Fig. 3. The value of sheet resistance was lowest at 500°C for 1 h both on mica and on glass. By increasing the annealing temperature, the variation was observed in the sheet resistance values when it comes to 500°C or higher in the case on the glass or 600°C or higher in the case on mica. Calculated resistivity was as low as 1.06×10^{-3} Ωcm at sheet resistance of 10.6 Ω/□ and the film thickness of 1 μm. RTA was carried out between 500°C and 540°C. Although the resistivity value was higher

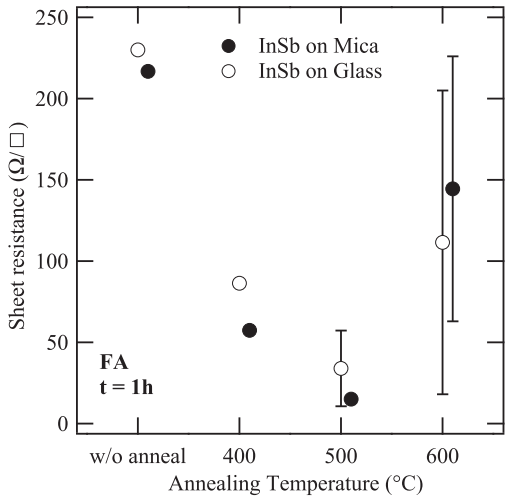

FIG. 3. Sheet resistance of InSb before and after FA.

in the case of RTA compared to the case of FA, uniformity of the film thickness and other physical properties such as In:Sb ratio are much more improved after RTA.

4. Hall mobility measurement

Fig. 4 shows results of the Hall electron mobility for InSb films on both mica and glass substrates before and after FA. 50 nm thick SiO_2 cap was deposited on InSb samples and they were annealed at 600°C. Hall electron mobility of InSb on mica was around 22,000 $cm^2/(Vs)$ and 2,000 $cm^2/(Vs)$ on glass before annealing. However, Hall mobility decreased after FA at 400°C for 1 h, for samples on both mica and on glass substrates. Further decrease in Hall mobility was observed after increasing the annealing temperature up to 500°C. It is speculated that composition of the InSb (i.e., atomic ratio of In:Sb) has changed at annealing after long time. Electron mobility (μ) has decreased due to the change of InSb composition. InSb layer did not remained and the sample was visibly transparent after annealing at 600°C. As the melting point of InSb is 525°C,[18] it is considered that InSb was vaporized at the temperature of 600°C.

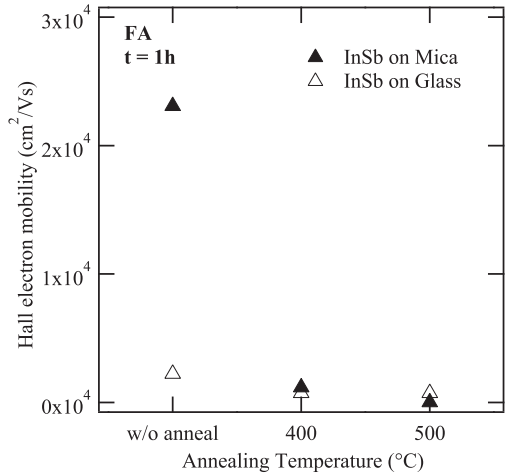

FIG. 4. Hall electron mobility of InSb before and after FA.

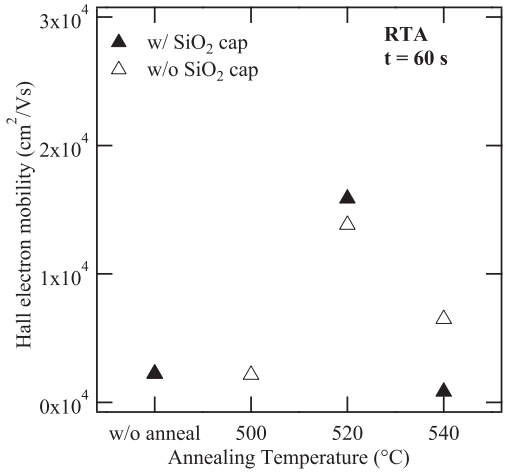

FIG. 5. Dependency of Hall mobility on RTA annealing temperature for InSb on glass substrate.

B. Rapid thermal annealing

As the Hall electron mobility of InSb decreased after FA, faster annealing method was considered to improve the crystallinity of InSb without changing InSb composition. It is expected that RTA may not change the InSb composition compared to FA. Electrical characteristics after RTA was studied. Annealing temperature and annealing time dependency of InSb on glass substrates were studied. Finally, InSb atomic composition was studied using energy-dispersive X-ray spectroscopy (EDS).

1. Hall mobility measurement

Fig. 5 shows the annealing temperature dependency of Hall electron mobility for InSb on glass substrate. Very high Hall electron mobility of about 15,000 $cm^2/(Vs)$ was obtained with the sample annealed at 520°C. As the melting point of InSb 525°C,[18] it is possible that InSb may start to vaporize and composition has changed at the temperature of 540°C.[19]

The highest mobility was obtained by annealing at 520°C. Annealing time dependency on Hall electron mobility was studied at 520°C from 0 s to 120 s (Fig. 6). Average Hall electron mobility of 23,000 $cm^2/(Vs)$ was obtained for the SiO_2 capped InSb films which annealed for more than 30 s. Highest Hall electron mobility around 17,000 was obtained with the uncapped InSb film annealed for

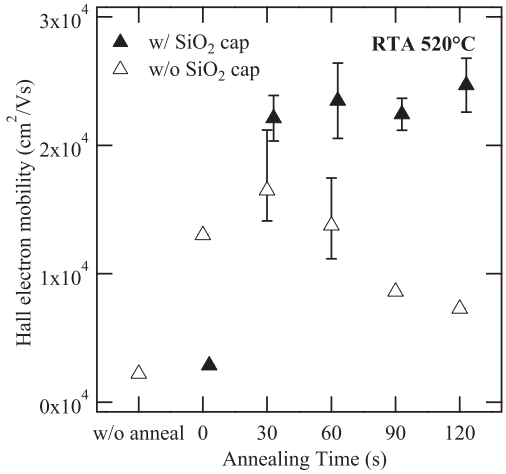

FIG. 6. Dependency of Hall mobility on RTA annealing time for InSb on glass substrate.

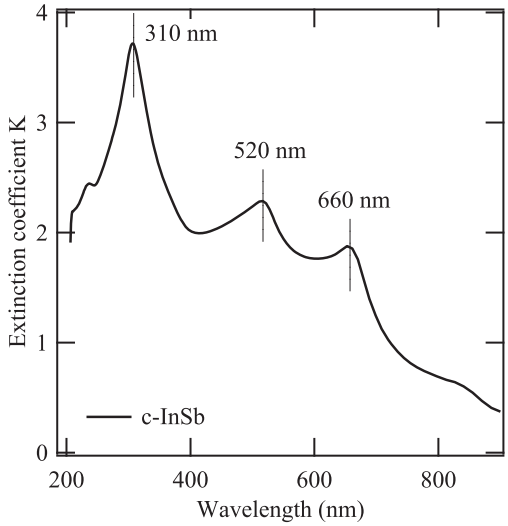

FIG. 7. Extinction coefficient of crystalline InSb (Source: Winelli database).

30 s. However, Hall electron mobility of uncapped InSb films reduced drastically when the annealing time is longer than 30 s. By increasing the annealing time, it is speculated that change of InSb composition or partial elimination by heat may causes the reduction in mobility.

By FA, it is possible to realize large grains when crystallization occurs by applying heat slowly to the InSb film. However, the remained defects concentration is high. By adopting RTA, the generated grain size is smaller than the grains after FA, while the defects concentration is low. By the crystallization using RTA, it is considered that lifetime and mobility increases mainly due to the reduction of defects. Effect of crystallization with less defects density is speculated as the dominant factor for the high carrier mobility of InSb films after RTA with keeping the constant composition of In and Sb. Therefore, it is considered that the dominant effect is basically constant composition for the poly-crystalline formation and after that or additionally high quality poly-crystal phase with low defects would be important.

2. Crystallinity evaluation by spectral reflectance

Fig. 8 shows the reflectance measurement results of 1m thick InSb films after RTA. Slight peaks around wavelengths of 310, 520 and 660 nm were observed after annealing with capping layer.

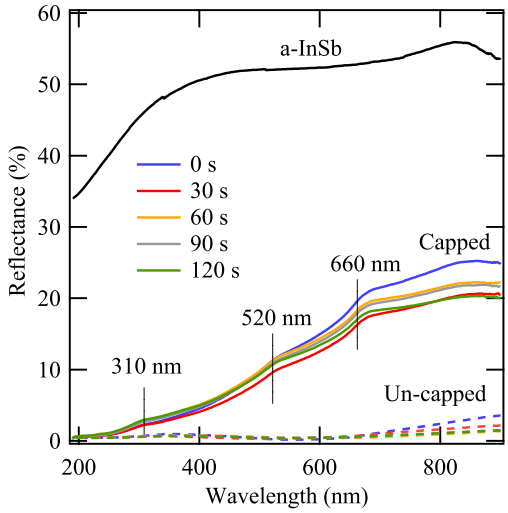

FIG. 8. Reflectance of 1 μm thick InSb films after RTA at 520°C.

TABLE I. EDS analysis of InSb.

	Atomic %				
Annealing time (s)[a]	*In*	*Sb*	*Si*	*O*	*In* : *Sb*
w/o anneal	48.0	47.3	0.2	4.6	1 : 1
0	38.0	30.8	2.0	29.2	1 : 0.8
30	40.7	29.4	0.5	29.5	1 : 0.7
60	39.9	29.8	0.6	29.7	1 : 0.7
90	35.1	28.5	0.7	35.7	1 : 0.8
120	37.9	28.2	0.4	33.6	1 : 0.7
Annealing time (s)[b]	*In*	*Sb*	*Si*	*O*	*In* : *Sb*
0	36.2	35.9	4.7	23.2	1 : 1
30	47.2	44.9	0.6	7.3	1 : 1.1
60	46.5	44.5	0.9	8.0	1 : 1
90	45.7	45.5	0.2	8.6	1 : 1
120	47.3	46.0	1.1	5.6	1 : 1

[a]w/o SiO_2 cap.
[b]w/ SiO_2 cap.

However, these peaks were hard to observe and the reflectivity values were less in the case of uncapped InSb films compared to capped InSb films. It is speculated that these peaks are correspondent to the extinction coefficient (k) peaks of c-InSb as in Fig. 7 and the capped InSb have crystallized.

3. In:Sb ratio deduced from EDS

Table. I shows the energy-dispersive X-ray spectroscopy (EDS) analysis results for both capped and uncapped InSb films before and after RTA. For the uncapped InSb, it appears that the percentage of Sb with respect to In is reduced after annealing. However, ratio of In vs Sb (1:1) is maintained when annealing by keeping SiO_2 cap. From this results, it is considered that the evaporation of Sb due to the annealing time may led the decrease of Hall electron mobility of uncapped InSb films. Studies on temperature dependence of the electron concentration in InSb show that electron concentration increases with the increase in temperature.[20] It is speculated that carrier concentration of InSb may have increased with the increase of RTA time.

III. CONCLUSIONS

Pre-annealed InSb films of 1 μm thickness, deposited on glass and on mica substrates using vacuum evaporation method were crystallized using FA or RTA. For InSb film on glass, Hall electron mobility value was about 2,000 $cm^2/(Vs)$ before heat treatment, after 30 seconds of RTA, the value increased up to about 18,000 $cm^2/(Vs)$. By capping with SiO_2, Hall electron mobility was increased further up to about 25,000 $cm^2/(Vs)$ after 60 seconds annealing. InSb film having a high mobility were realized by RTA on glass at a temperature lower than the melting point (525°C) of the single-crystal InSb. High mobility devices such as high resolution IR detectors, magnetic field sensors and ultra-speed transistors are expected by crystallizing the InSb film on the glass by RTA.

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