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The effect of magnetic field direction on thermoelectric and thermomagnetic coefficients of undoped single crystalline InSb at room temperature

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The effect of magnetic field direction on thermoelectric and thermomagnetic coefficients of undoped single crystalline InSb at room temperature

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Abstract. Thermoelectric and thermomagnetic coefficients were calculated for n-type undoped InSb single crystals through a temperature range from 10°C up to 80°C and magnetic fields from -0.6T to 0.6T. The thermoelectric Seebeck coefficient varied only with the temperature gradient, while the thermomagnetic Nernst coefficient varied with both the temperature gradient and the magnetic field. This paper also investigated the effects of the incident angle of magnetic field on the InSb sample surface with regard to the values of thermoelectric and thermomagnetic coefficients; the results showed that thermoelectric and thermomagnetic coefficients were independent of magnetic field direction.

1. Introduction

The Global concern about renewable energy is rising as traditional fuels such as fossil fuels, begin to run out. One of the proposed replacement technologies is the conversion of waste heat into electrical power with or without an applied magnetic field, a phenomenon known as called thermomagnetic (TM) or Thermo-magneto electric (TME) generation, whereby a thermomagnetic material can convert a temperature gradient into electrical power. Transverse TM effects are particularly valuable when used in energy conversion as shown in recent studies [1-5]. Many researchers have thus attempted to obtain electrical power from thermomagnetic materials; however, several have achieved only limited success . This paper thus attempts to use a pulse system (controlling maximum pulse value by changing the magnetic field direction) to add another control system to cool the system or, by shutting down the system, reduce energy losses, thus improving the operating conditions of such electro-magnetic machines and increasing the safety of use in motors, generators and transformers.

InSb is one candidate for this among the Nernst elements [6], with important applications in infrared, optical, microwave, and millimetre-wave devices [7], medical applications [8], high mobility transistors [9], thermo-photovoltaic cells, high-speed devices and magnetic sensors [10].

Where electrical or thermal currents flow in a solid material perpendicular to an external magnetic field, four transverse effects exist.

When the electric current passes longitudinally under magnetic field perpendicular to that current, it produces a potential gradient (Hall-effect) and a temperature gradient (Ettingshausen-effect). When a thermal current passes longitudinally in this manner, it also produces a potential gradient (Seebeck-effect) and a temperature gradient (Righi-Leduc effect). The Nernest coefficient, N, is thus defined as:

$$\delta = \Delta \boldsymbol{V} / \Delta \mathrm{T} \quad (1)$$

$$|N| = \frac{E_y/B_z}{dT/dx} \quad (2)$$

$$\boldsymbol{\nabla_y V = N B_z \nabla_x T} \quad (3)$$

where δ is the Seebeck coefficient, ΔV and ΔT are the voltage and temperature differences between the cool and hot sides, N is the Nernst coefficient, $\mathbf{E_y}$ is the y-component of the electrical field, $\mathbf{B_z}$ is the magnetic field, $\boldsymbol{dT/dx}$ is the temperature gradient on the x-axis, $\boldsymbol{\nabla_x T}$ is the temperature gradient in the x-direction, $\nabla_y \boldsymbol{V}$ is the open circuit induced potential gradient in the y-direction, and $\boldsymbol{B_z}$ is the magnetic field in the z-direction.

Experimentally, more than one transverse effect is expected to occur simultaneously, and all of these must be measured. Thus, it is necessary to isolate the desired effect (the Nernst voltage) from the other effects. M. R. El-Saden and et.al [11] addressed this problem directly, while previous researchers [2, 6, 9, 11, 12, 17, 20] omitted the effect of the incident angle between the sample surface and the magnetic field. This paper thus seeks to examine the effect of the incident angle of magnetic field on InSb sample surface with changes in the values of thermoelectric and thermomagnetic coefficients, as well as focusing on separating the voltages caused by the presence of thermos and magnetic changes, in order to improve and increase the Nernst coefficient.

Indium Antimonide (InSb) is a candidate thermo-magnetic element to be used as a thermo-magnetic sensor at room temperature due to its narrow band gap of 0.18eV and its high mobility.

2. InSb Material (Samples)

2.1 Sample Properties

One of the most promising Nernst materials is InSb due to it having the largest carrier mobilities, a high mobility ratio (ratio between electron mobility and hole mobility), and a narrow band gap of about 0.17 eV [12,13,14]. InSb is a III-V semiconductor with the highest electron mobility ($\mu_e \approx 7700$ $cm^2.V^{-1}.S^{-1}$) among the materials in its group [15].

Intrinsic semiconductors offer a promising approach to developing higher performance thermomagnetic materials. The effect of temperature on the performance of InSb occurs where temperature changes reach the material’s to intrinsic regions. This offers further evidence that InSb is thermomagnetically favourable, as InSb transits from the extrinsic region to the intrinsic region in the region close to room temperature [6, 16-18].

2.2 Samples for Investigation

Undoped InSb (111) single crystalline wafer with dimensions of 50.5mm diameter and 962- to 977μm thickness, as supplied by Wafer Technology LKTD, was used to create n-type semiconductors with carrier concentration $7.2\times10^{+13} – 1.90\times10^{+14}$ cm^{-3}. The samples cut from this wafer were in two different shapes: bridge and rectangular.

2.3 Sample Description

N-type undoped InSb (111) single crystal is considered to investigate the transport coefficient under a magnetic field.

The selected shapes of the samples thus required several particular characteristics:

1. The width of the sample has to be small enough relative to the length to obtain higher values for the Nernst coefficient and to minimse geometrical magnetoresistance.
2. The width at the top and bottom of the sample should be wide enough to make good attachments to the cooling or heating bath.
3. The shape should have “arms” to prevent warping flux lines of current [2, 11].

Most authors suggest the use of the Bridge shape for such samples[8-11,14], with some using the Fat-Bridge shape[10, 14]. In this paper, two sample types were prepared, one as Bridge shape and the other rectangular, as shown in figure 1.

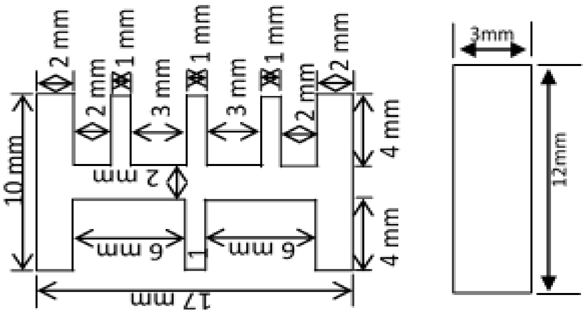

Figure 1. The design of a: Bridge shape and b: rectangular shape.

The first sample type was cut using a laser cutter and the other using a diamond disk cutter, with accuracy being within ±10 μm and 0.01 mm respectively.

3. Experimental Work

The thermoelectric and thermomagnetic effects of InSb under an external magnetic field up to 0.6Tesla, generated by an electromagnetic device, were investigated.

A thermoelectric module was used as a hot side and a copper plate as a heat sink. Thermal compound was put between both the hot and cool sides, and the sample; this has high thermal conductivity, > 4.5 W/m-K, thus ensuring that heat could flow uniformly. A thermocouple of type K was put inside a grove made on the inert surface of the copper plate on both the hot and cool sides to monitor the temperature; figure 2 shows a schematic diagram of the sample placement over the hot and cool sides.

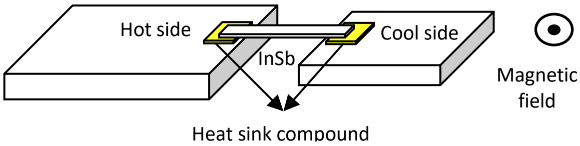

Figure 2. Schematic diagram of sample position.

All sample contacts were connected to 37-gauge lead wires (0.111mm diameter, pure copper) using silver paint in order to provide proper contacts for the thermal and electrical currents. All components were assembled on a printed circuit board (PCB) to investigate the thermoelectric and thermomagnetic effects at room temperature and under a magnetic field, as in [19].

3.1 DC Magnetic Field

An electromagnet (4-inch diameter pole) was used to induce a magnetic field when a DC current passed through its coils. The material such a magnet's core is usually iron.

Induced magnetic flux density depends on the spacing between poles and the DC current value. The maximum field from this device is less than 0.6 T for a 3 cm gap between poles, however, as shown in figure 3.

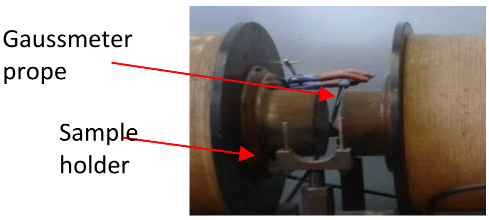

Figure 3. Electromagnetic device.

The PCB was rotated using a holder to investigate the effects of changing the incident angle of the magnetic field on the InSb sample surface.

4. Results

4.1 Seebeck Voltage

The Seebeck voltage was measured between the hot and cool sides for all samples, figure 4 shows the relationship between Seebeck voltage and temperature difference for undoped InSb single crystalline with Bridge shape (USB) and undoped InSb single crystalline with rectangular shape (USR) samples under 0.3T.

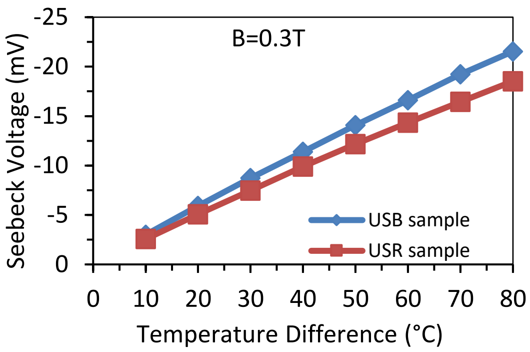

Figure 4. Seebeck voltage as a function of temperature difference for USB and USR samples.

The Seebeck voltage for USB is higher than for USR, the latter of which decreased gradually (i.e. became more negative) with the increased temperature difference.

The Seebeck coefficient for the USR sample showed similar behaviour to the USB sample. However, the former sample has agenerally lower values than the latter, as in [19].

Figure 5 shows the relationship between the Seebeck voltage and the temperature difference for USB samples at different degrees of incident angle between the magnetic field (0.3T) and the sample surface.

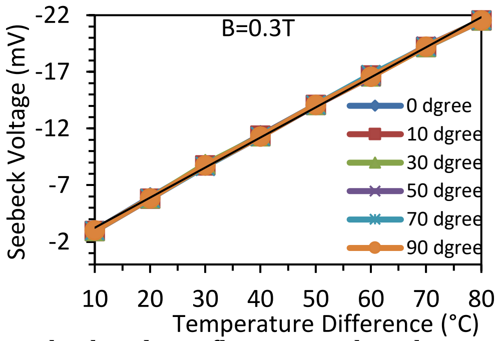

Figure 5. Seebeck voltage as a function of temperature difference for USB at different incident angle between InSb sample surface and magnetic field (0.3T).

The Seebeck voltage fluctuates when the incident angle of the magnetic field under 0.3T to the InSb sample surface changes.

4.2 Seebeck Coefficient

The Seebeck coefficient for the sample under a magnetic field up to 0.6T and with temperature differences from 10°C to 80°C (in 10°C increments) was calculated, figure 6 shows the variation of Seebeck coefficient with magnetic field levels for USB and USR .

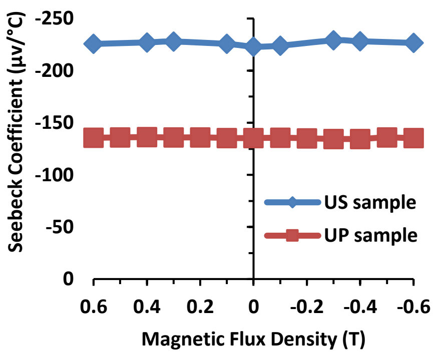

Figure 6. Seebeck coefficient as a function of magnetic field for USB and USR samples.

The Seebeck coefficient for the bridge shape decreases gradually (becomes more negative) with increases in magnetic flux density until 0.3 T, then fluctuates slightly up to 0.6T.

The Seebeck coefficient for the USR sample fluctuates with increasing magnetic flux density; for more details see [19].

Figure 7 shows the relationship between the Seebeck coefficient and the temperature difference for USB samples at different degrees of incident angle between the magnetic field (0.5T) and the sample surface.

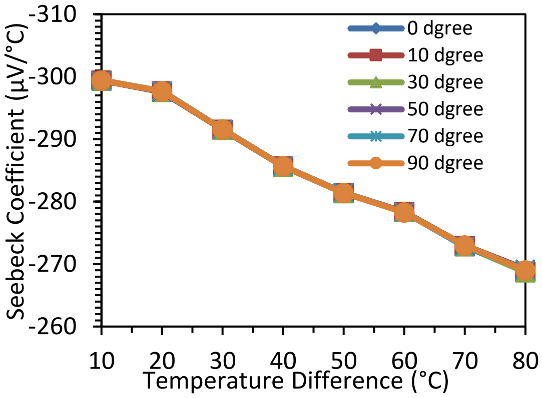

Figure 7. Seebeck coefficient as a function of temperature difference for USB samples at different incident angles between the sample surface and magnetic field (0.5T).

The Seebeck coefficient fluctuates as the incidence angle of the magnetic field under 0.5T to the InSb sample surface changes.

4.3 Transverse Voltage

The transverse voltage was measured between the two middle connected points under the same conditions. figure 8 shows the variation of the transverse voltage with temperature difference at various magnetic field levels for the USB sample.

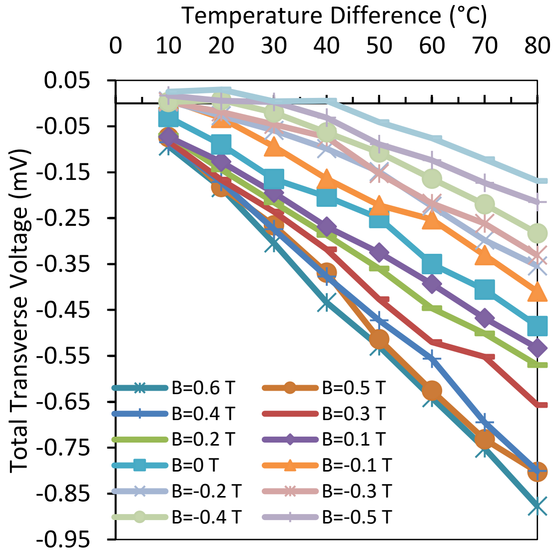

Figure 8. Transverse voltage as a function of temperature difference for USB sample.

The total transverse voltage decreased slightly (became more negative) with increased temperature differences for all magnetic field levels. It increased gradually (became less negative) with increases in the magnetic field for the reversed magnetic field and vice versa. This is due to the total transverse voltage being a summation of three parameters (misalignment, and Nernst and Righi-Leduc voltages). To understand this combined effect more completely, a discussion of the individual effects of each parameter is required, as offered in [19].

The total transverse voltage for the USR sample shows similar behaviour to the UBS sample.

However, the former has lower values than the latter sample; for more details, see [19].

Figure 9 shows the variation of transverse voltage with temperature differences at various magnetic field levels for the USB sample at different degrees of incident angle between the magnetic field and the sample surface.

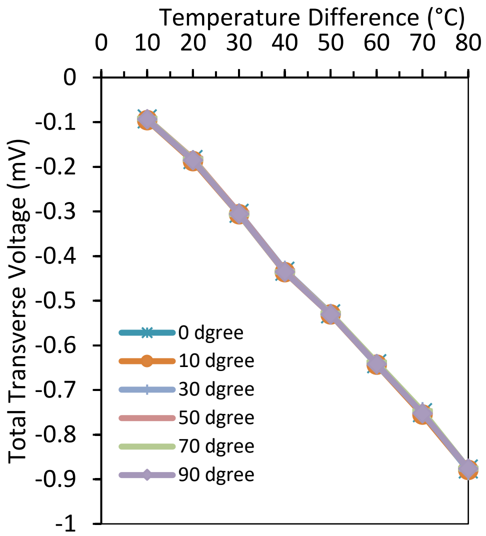

Figure 9. Transverse voltage as a function of temperature difference for USB samples at a different incident angles between the sample surface and magnetic field (0.6T).

The total transverse voltage fluctuates with changes in the incident angle of the magnetic field under 0.6T to the InSb sample surface.

5. Conclusion

The Seebeck voltage, coefficient and transverse voltage are independent of the incident angle of the magnetic field to the InSb sample surface. This result is in full agreement with [2, 6, 9, 11, 12, 17, 19], which do not consider this the variable; however, other researchers [4, 20-24] have studied this variable's on thermoelectric and thermomagnetic coefficients, and suggest that the maximum values of thermoelectric and thermomagnetic coefficients are achieved when the applied magnetic field is perpendicular to the temperature gradient.

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