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Heat flux flow of PN-junction gallium arsenide semiconductor device

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Abstract

Temperature profile inside semiconductor device is a key issue to realize its maximum performance. One of the simplest the PN junction device is a diode, and the resistivity of the depletion layer is high and the heat is generated mainly in the area for usual diodes. If the temperature of the depletion layer is high, the performance of the device is degraded, especially for the laser diode. The heat flux is transferred from the depletion layer mainly by thermal conduction for high thermal conductivity material. However, the thermal conductivity of single crystal gallium arsenide (GaAs) is low as 50 W/Km, and moreover we must consider the Peltier heat flow near the PN-junction area because the directions of the heat flows of N- and P-type's are to the depletion layer. In order to solve this problem, we measure the thermal conductivity, the Seebeck coefficient and the electrical resistivity of GaAs, and we estimate the temperature of the depletion layer by the computer simulation.

Introduction

Diode is a common semiconductor device, and this is based on the structure of PN-junction [1]. Gallium arsenide based PN-junction device is used to make solid-state laser for the optical fiber communication [2], and therefore it is a key device for the modern life in the present time. The temperature of GaAs laser diode is controlled within 1/100 K to keep stable emission and its wavelength. This is the basis of wavelength division multiplex (WDM) [3], and the temperature control is a key technology for the laser diode, and the Peltier module is used with the laser diode. The temperature of the device is determined by both of the heat generation, heat transfer and the light emission. Therefore, if we would estimate the performance of light emitting diode, we must know and control the temperature profile inside the diode precisely.

Usually we use the numerical software to estimate the temperature profile inside the semiconductor device, and it is called a numerical device stimulator [4, 5, 6]. The software solves the heat balance equation to obtain the temperature profile, and it includes the physical processes of the Joule heating by electric current, the heat transfer by the thermal conduction. But we know a different process of the heat transfer by the electric current as Peltier heat flow, and unfortunately it is not included in the present numerical software because the thermoelectric effect is not thought to be large. However, it is important to estimate the temperature of the PN-junction part precisely, especially for the laser diode, we must consider the Peltier heat flow in detail because the emission and the wavelength of the light from the GaAs diode depend on the temperature of the depletion layer. In order to fix this problem, we measured the Seebeck coefficient of the single crystal GaAs for the laser diode at first. We calculate the temperature profile of the diode by ANSYS [7] in this paper.

Heat transfer model of diode by thermoelectric effect

Figure 1 shows the diode structure, its symbol, its current direction and the directions of Peltier heat flow.

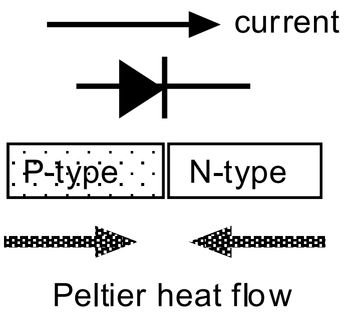


Fig. 1 Diode structure, symbol, current direction and the direction of Peltier heat flow

The magnitude of diode current is limited by the temperature because when the temperature is high, the crystal of diode material would be destroyed by the electric current. Therefore, we keep the diode low temperature, and use the cooling system for it. Usually when the cooling system is effective, we can use the diode in high current. This means that when we keep the laser diode low temperature, we can expect that the light is strong. The maximum temperature part of the diode is usually located around the depletion layer of PN-junction because the resistivity of the depletion layer is quite high and we cannot cool the depletion layer directly. Radiation fin is usually connected to the electrode of the diode for the cooling, and it means that we can cool it at the end of the diode or the diode electrode. As is shown in Fig. 1, since the directions of Peltier heat flows are toward the depletion layer in both sides of P- and N-types of semiconductors, the temperature of the depletion layer will be increased by the thermoelectric effect. Therefore, if the Seebeck coefficient is high, the heat fluxes from the both sides to the depletion layer is high by Peltier effect, and therefore the temperature of the depletion layer of the laser diode will be high. This phenomenon can reduce the performance of the laser diode. This situation is common for all diodes.

Measurement of transport parameters of Gallium arsenide

We prepared two samples to measure the transport coefficients of the single crystal GaAs. This is the laser diode grade material, and two samples were obtained from the same ingot and they are N-type material. The carrier density of the sample is 1.3x10^{18} cm^{-3}. The size of the sample is the length of 20 mm, the wide of 4 mm and the thickness of 1 mm. The electrical resistivities of the samples are shown in Fig. 2.

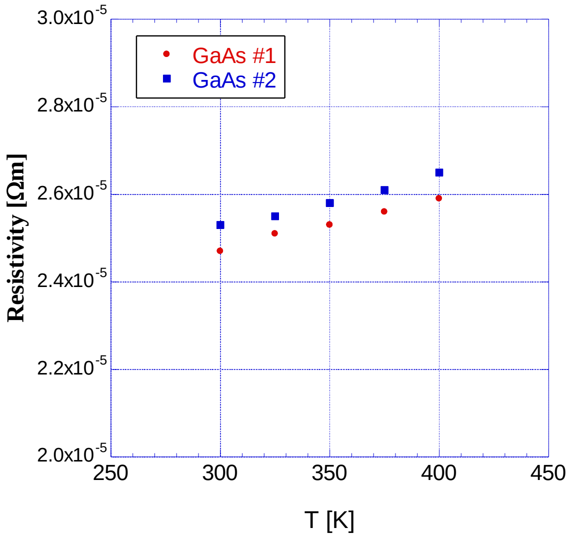


Fig. 2 Temperature dependences of resistivity of the single crystal GaAs

The resistivities of two samples are almost same, and they are the same order of the other reported data [8].

Figure 3 shows the temperature dependence of the thermal conductivities. The temperature difference of the samples is around 8 K to measure the thermal conductivity. Unfortunately, we cannot measure the sample #1 in this time. The reported value of the thermal conductivity is around 50 W/Km [9], and the thermal conductivity increased with the increase of the temperature. But the measured values are smaller than the reported value, and the temperature dependence is also different from the report. The thermal conductivity is decreased with the increase of the temperature around the room temperature.

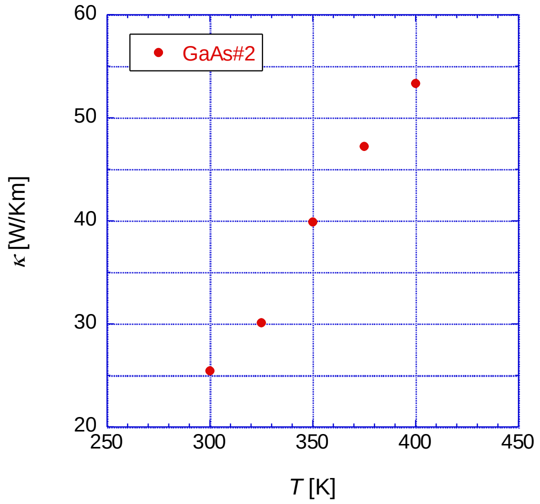


Fig. 3 Temperature dependences of thermal conductivity of the single crystal GaAs

Finally, we measure the Seebeck coefficients as shown in Fig. 4. The temperature difference of the sample is around 1.5 K to measure the Seebeck coefficient in this time. The values of two samples are similar to each other, and their temperature dependences are also similar. This data is consisted with the reported values in the range of the carrier density in ref. [10].

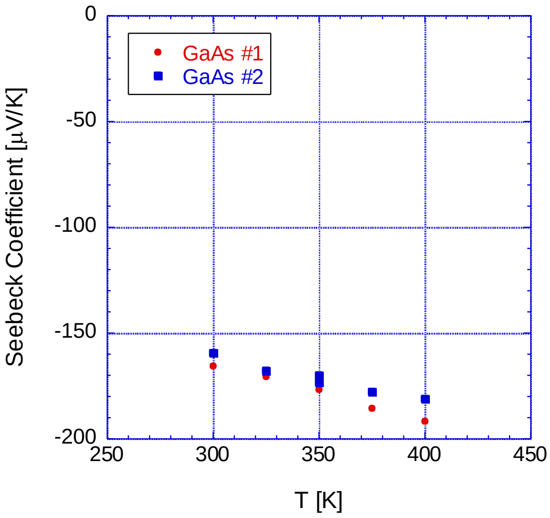


Fig. 4 Temperature dependences of Seebeck coefficient of the N-type single crystal GaAs.

Numerical calculation by ANSYS

After we measured the transport parameters of the single crystal GaAs, we did the numerical calculation by ANSYS [7] to estimate the temperature profile of the diode. The numerical model of the calculation is shown in Fig. 5.

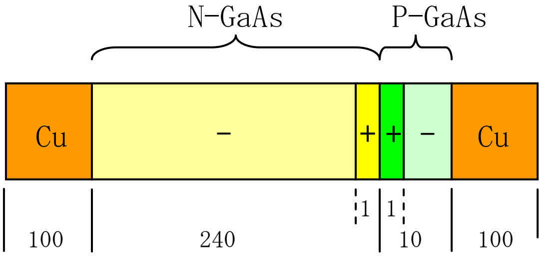
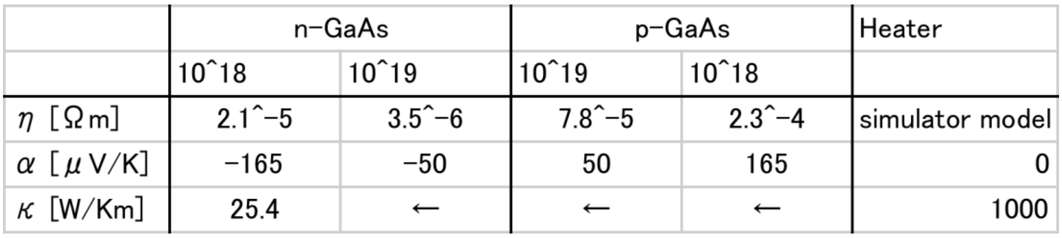


Fig. 4 Numerical model of GaAs laser diode.

The cross-section of the diode is 100 x 100 μm, and the numbers in the figure show the lengths of the parts in μm. The both ends are the copper electrodes and are shown as Cu. N-type GaAs is located left-hand side, and the minus sign (-) shows the low carrier density part, and it is 10^{18} cm^{-3}, and the plus sign (+) shows the high density part and it is 10^{19} cm^{-3}. The P-type parts are located in right-hand side, and the lengths are shown in figure, and the carrier densities are the same as the N-types'. This is the typical structure of the laser diode. The length of the depletion layer is set to be zero in this model because it is thin, but we insert the heater into the PN-junction face to simulate the depletion layer. The heat generation of the heater is proportional to the square of the current. The boundary condition of the temperature is set to be 300 K at the end of the electrode of N-type side.

However, in order to calculate the temperature in the model, we should make some assumptions to estimate the transport parameters in different carrier density regions of the model. We only measure the transport parameters for one sample, and its density profile is uniform. And therefore, we did not have the data of the transport parameters in different carrier density. Therefore, we should make the assumption for the different carrier density. Instead of the measurements, we estimated the electrical resistivity from the measured values along the ref. [8]. This is based on the relation with resistivity and impurity concentration. We also assumed the Seebeck coefficient in different carrier density from the measured values along ref. [10]. The thermal conductivity is assumed to be constant for the carrier density in the model both for N-type and P-type GaAs because the phonon process is major than that of electronic process for the thermal conduction. We could not also measure a P-type sample in this time, and unfortunately we also cannot find the Seebeck coefficient of P-type samples in the academic journals. Therefore, we assumes that the absolute value of the Seebeck coefficient is the same as the N-type’s for the same carrier density. Finally, the transport parameters of the model in Fig. 4 are summarized in Table 1.

Table 1 Transport parameters and heater model for numerical calculations



	n−GaAs		p−GaAs		Heater
	10ˆ18	10ˆ19	10ˆ19	10ˆ18	
η [Ωm]	2.1ˆ−5	3.5ˆ−6	7.8ˆ−5	2.3ˆ−4	simulator model
α [μV/K]	−165	−50	50	165	0
κ [W/Km]	25.4	←	←	←	1000

The effective resistivity of the heater is set the numerical calculation result of the device simulator [6], and its length is 1 μm. The heat generation is proportional to the square of the current.

The calculation results of the junction temperature are shown in Fig. 5.

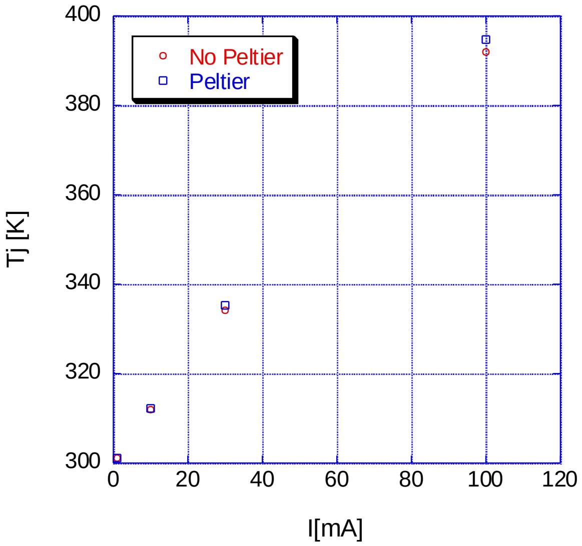


Fig. 5 Calculation results of the junction temperature by ANSYS [7].

We did two types of the calculations. One include the Peltier effect, and the calculation results are shown as the squares. The other does not include the Peltier effect, and they are shown as the circulars in the figure. When we include the Peltier effect, the temperature is higher than the model's that does not include the Peltier effect. These results are consisted with the Fig. 1, and the temperature difference depends on the magnitude of the current. When we apply large current, the temperature difference is 0.43 K at the current of 10 mA, and 2.53 K at the current of 100 mA. These differences are 100 times larger than the values of the keeping temperature for the stable operation of the laser diode as mentioned in Introduction.

Discussion and Conclusion

The calculation results shows that we must include the Peltier effect to estimate the temperature at the depletion layer precisely, and it is important to estimate the performance of the laser diode as shown in Fig. 5. However, we should continue to perform the experiment to obtain the actual parameters for the P-type GaAs. We also should pay attention to make a precise model for the calculation, too. And we should take into account the Peltier effect for all diodes. Finally the numerical simulator must include the Peltier effect in the software.

As mentioned in Fig. 4, the Seebeck coefficient is change within short length, and therefore we should take into account the Thomson effect because the gradient of the

Seebeck coefficient might not be small. This situation is similar to the FGM, but it is not same as the concept of the FMG because the transport parameters are measured and estimated in the condition of charge neutrality for the FGM, but the PN-junction is not always keep the charge neutrality. The impurity profile around the depletion layer is not changed by the current, and the charge neutrality is kept even for the presence of the electric current without the area of electrode contact in the thermoelectric module. However, the carrier density in the depletion layer depends on the magnitude of the current in spite of the impurity density constant. Therefore, we must continue to discuss and research the model of the calculation.

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