

Leakage Current Density and Characteristic Temperature Determination for PbSe/PbSrSe Multiple Quantum Well Structure

Majed Khodr

Department of Electronics and Communications Engineering,
American University of Ras Al Khaimah, United Arab University,
P.O. Box 10021, Ras Al Khaimah, UAE

Abstract: The characteristic temperature calculations and dependency on quantum efficiency was analyzed for $\text{Pb}_{0.934}\text{Sr}_{0.066}\text{Se}$ multiple quantum well structure at three temperature ranges; $77\text{ K} \leq T_0 \leq 150\text{ K}$, $150 \leq T_0 \leq 300\text{ K}$ and $77\text{ K} \leq T_0 \leq 300\text{ K}$. Inclusion of theoretical values for the quantum efficiency due to auger recombination and leakage current reduces the characteristic Temperature (T_0) in these ranges. We compared the effects of including the theoretical quantum efficiency and an experimentally determined ones on the characteristic temperature values at a fixed cavity length of $600\text{ }\mu\text{m}$. When results were compared to experimental data, it was concluded that there is a leakage current above the barrier due to thermionic emission in the high temperature range $150 \leq T_0 \leq 300\text{ K}$. We estimated these additional values to be 246, 1353 and 5423 A cm^{-2} at 200, 250 and 300 K, respectively. These are high values and hence, more work is needed to understand the thermionic emission process to improve on the performance of this material system and similar ones.

Key words: Characteristic temperature, thermionic emission, leakage current, lead salts, cavity

INTRODUCTION

Mid-IR lasers can have very high manufacturing costs due to the use of GaSb and InAs growth substrate technologies as is the case with ICL fabrication. There is thus, a need for a mid-IR laser technology that can match the low power consumption of ICLs but fabricated using a technology that will allow low unit cost production methods.

The first mid-IR lasers developed were based on the narrow band gap IV-VI compound semiconductor family of materials. An attractive aspect of IV-VI semiconductor materials is that they can be grown with high crystalline quality on industry standard silicon substrates. Such a growth technology can be readily scaled to enable low unit cost production thus making possible the commercialization of low cost sensors for the widest possible distribution.

The experimental and theoretical results to date suggest that for wavelengths of about 3-30 μm , lead salt lasers will operate at significantly higher temperatures than those from other materials.

In these mid infrared and far infrared regions, these structures may play a key role in IR spectroscopy applications such as breath analysis instruments, air pollution monitoring and IR integrated optics and IR telecommunication devices. These important applications are driving the need for a better understanding of IV-VI

quantum well lasers and a new experimental interest emerged in PbSe/Pb 0.934 Sr 0.066 Se mid-IR tunable quantum well laser structures (Shen *et al.*, 2002; McCann *et al.*, 2007).

This research is a continuation to earlier publications to shed the light on this material system (Khodr, 2013). We analyze and calculate characteristic temperature as a function of quantum efficiency and estimate the values of the leakage current over the barrier which can be due to the thermionic mission effect. We will show that the threshold current density at room temperature has very high values due to current leakage over the barrier due to thermionic emission. This could be one of the reasons that growing and operating the proposed system at room temperature were not successful until the writing of this study. The study was done in three temperature ranges; $77\text{ K} < T < 150\text{ K}$, $150\text{ K} < T < 300\text{ K}$ and $77\text{ K} < T < 300\text{ K}$.

MATERIALS AND METHODS

The material system under investigation is PbSe/Pb_{0.934} Sr_{0.066} Se MQW with PbSe as the well material with width of 7 nm and Pb_{0.934} Sr_{0.066} Se as a barrier material with thickness of 70 nm, number of wells of 7, index of refraction of the well material is 4.865 and that of the barrier material is 4.38. The index of refraction values are assumed constant and independent on temperature and wavelength (Khodr, 2013).

The temperature dependence of the threshold current density J_{th} depends on the temperature dependence of the gain, internal losses and quantum efficiency. When Auger recombination is the dominate nonradiative recombination mechanism, the quantum efficiency may then be written as $\eta = 1/(1+\tau_r/\tau_a)$ where τ_r is the radiative lifetime and τ_a is the Auger lifetime (Khodr, 2013). Inclusion of Auger recombination in addition to the temperature dependence of the gain in the calculations of J_{th} results in a temperature variation as $\exp(T/T_0)$ where T_0 is the characteristic temperature in a specific temperature range (Casey, 1984). It is desired to have higher characteristic temperatures. Higher values of T_0 imply that the threshold current density and the external differential quantum efficiency of the device increase less rapidly with increasing temperatures. This translates into the laser being more thermally stable.

First, we calculated the leakage current density by studying the relationship between threshold current density and temperature at a fixed cavity length of 600 μm including the effects of quantum efficiency. Second, we studied the relationship between the characteristic temperature T_0 and laser cavity length L in three temperature ranges; $77\text{ K} \leq T \leq 150\text{ K}$, $150 \leq T \leq 300\text{ K}$ and $77\text{ K} \leq T \leq 300\text{ K}$.

RESULTS AND DISCUSSION

We studied the relationship between the threshold current density as a function of temperature where cavity length was fixed at 600 μm . In Fig. 1, the data calculations for the lower curve assumed unity quantum efficiency and the upper curve is for the theoretically calculated quantum efficiency. As noticed in the figures the threshold current density values increases as a function of temperature at a fixed cavity length. Including the effects of quantum efficiency increase the threshold current values even further at a fixed cavity length and temperature.

Figure 1 can be used to calculate the characteristic Temperature (T_0) in the temperature ranges of interest by best fitted each curve into a straight line to determine T_0 in the temperature range of interest. In Fig. 1, we best fitted each curve into two straight line segments to determine T_0 in two ranges $77\text{ K} \leq T_0 \leq 150\text{ K}$ and $150 \leq T_0 \leq 300\text{ K}$. Assuming quantum efficiency to be equal to one, T_0 was found to be equal to 78 K (correlation coefficient $R^2 = 1$) for the $77\text{ K} \leq T_0 \leq 150\text{ K}$ range and 138 K ($R^2 = 0.9983$) for the $150 \leq T_0 \leq 300\text{ K}$ range. Including the effects of quantum efficiency T_0 value dropped to 48 K ($R^2 = 1$) for the $77\text{ K} \leq T_0 \leq 150\text{ K}$ range and to 101 K ($R^2 = 0.9948$) for the $150 \leq T_0 \leq 300\text{ K}$ range. Also, we best fitted the data to straight line (not shown in the figure) in

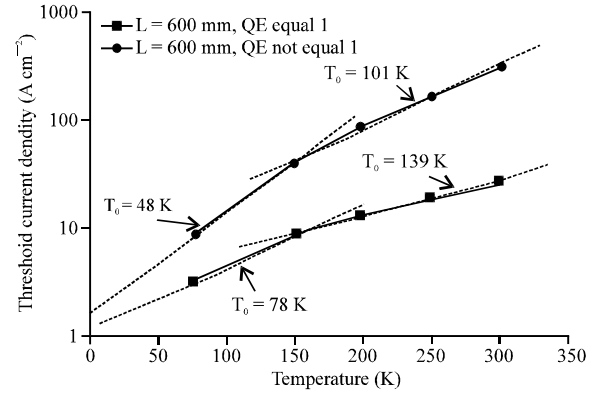


Fig. 1: The lower curve for $\eta = 1$ and the upper curve for $\eta \neq 1$. The characteristic temperature calculations in two temperature ranges; $77\text{ K} < T < 150\text{ K}$ and $150\text{ K} < T < 300\text{ K}$

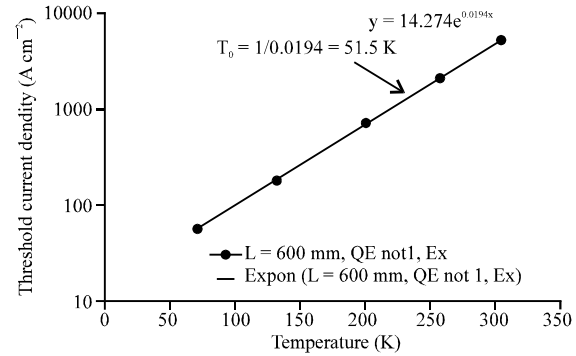


Fig. 2: Including the experimental quantum efficiency and best fitting the data to an exponential function resulted in a characteristic temperature value of 51.5 K in the temperature range; $77\text{ K} < T < 300\text{ K}$

the range $77 \leq T_0 \leq 300\text{ K}$ and found T_0 to be equal to 105 K ($R^2 = 0.9791$) and 64 K ($R^2 = 0.9829$) for $\eta = 1$ and $\eta \neq 1$, respectively.

In Fig. 2, we included the experimental values for the quantum efficiency from Findlay *et al.* (1998) and best fitted the data to calculate T_0 in the $77 \leq T_0 \leq 300\text{ K}$ for cavity length of 600 μm . The characteristic temperature value T_0 was found to be equal to 51.5 K ($R^2 = 0.9586$). This value is different from the values found in Fig. 1 for the same temperature range and cavity length. However, it is very close to T_0 value of 48 K found in the low temperature range $77\text{ K} \leq T_0 \leq 150\text{ K}$ and including quantum efficiency. Therefore, it is concluded that there is an additional thermionic current density term that is related to the leakage current above the barrier and affecting the data in the high temperature range $150 \leq T_0 \leq 300\text{ K}$. We estimated these additional values of the threshold current

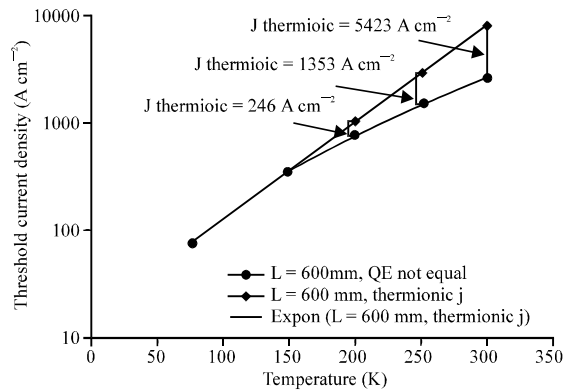


Fig. 3: The estimated threshold current values due to thermionic effects at different temperatures were found to be 246, 1353 and 5423 A cm⁻² at 200, 250 and 300 K, respectively

density at temperatures of interest as shown in Fig. 3. These values due to thermionic effects at different temperatures were found to be 246, 1353-5423 A cm⁻² at 200, 250 and 300 K, respectively.

CONCLUSION

In conclusion, the system under investigation is a very interesting one but more work is needed to overcome the temperature effects on the thermionic current that is leaking above the barrier. This high value at room temperature will limit the operation of this device to very low temperatures.

REFERENCES

- Casey Jr., H.C., 1984. Temperature dependence of the threshold current density in InP-Ga0. 28In0. 72As0. 6P0. 4 ($\lambda = 1.3 \mu\text{m}$) double heterostructure lasers. J. Appl. Phys., 56: 1959-1964.
- Findlay, P.C., C.R. Pidgeon, R. Kotitschke, A. Hollingworth, B.N. Murdin, C.J.G.M. Langerak and G. Springholz, 1998. Auger recombination dynamics of lead salts under picosecond free-electron-laser excitation. Phys. Rev. B., 58: 12908-12908.
- Khodr, M., 2013. Effects of quantum efficiency on PbSe/PbSrSe multiple quantum well structures. Proceedings of the International Society for Optics and Photonics SPIE NanoScience+Engineering, September 26, 2013, San Diego, California, United States, pp: 88160P-88160P.
- McCann, P., K. Namjou, C. Roller, G. McMillen and P. Kamat, 2007. IV-VI semiconductor lasers for gas phase biomarker detection. Proceedings of the International Conference on Society for Optics and Photonics Optics East 2007, September 25, 2007, University of Oklahoma, Norman, USA., pp: 675603-675603.
- Shen, W.Z., H.F. Yang, L.F. Jiang, K. Wang and G. Yu *et al.*, 2002. Band gaps, effective masses and refractive indices of PbSrSe thin films: Key properties for mid-infrared optoelectronic device applications. J. Appl. Phys., 91: 192-198.