An investigation of MWIR, AlInSb LEDs based on double heterostructures and multiple quantum wells

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Abstract-Mid-infrared LEDs based on AlInSb double heterostrucutre and multiple quantum well active regions have been simulated and investigated using the SimuLED software package from STR. The simulation results indicate that the double heterostrucutre and multiple quantum well active regions offer higher carrier injection efficiency and energy conversion. This translates into an output power and wall-plug efficiency that are three and two times higher, respectively, than a conventional homojunction active region.

Index Terms—Mid-infrared, Light emitting diodes (LEDs), Electroluminescence (EL), Quantum wells

I. INTRODUCTION

Semiconductor materials such as antimonide emitting in the 3-5 µm mid-infrared band are of great interest for the development of a low-cost photonic technology for the next generation of miniature and energy-efficient CO, CO_2, CH_4 gas sensors [1]. A well-established and cost effective approach is to directly grow the antimonide-based epilayer on a GaAs substrate. A buffer layer several µm thick is grown on top of the wafer to accommodate the large lattice mismatch [2]. Standard epilayer designs for LEDs employ a homojunction active region in combination with a relatively wide bandgap barrier between the active region and p-doping layer to reduce carrier leakage [1, 3, 4]. However, the carrier leakage in a homojunction design is still a major problem because of the efficiency droop under a high current density [5]. Here, we report on an investigation of multiple quantum well (MWQ) heterostructures as a means of increasing the efficiency of the mid-IR LEDs.

The carrier injection efficiency and carrier concentration distributions on the epitaxial structures with double heterostrucutre (DH) and MQW active regions were investigated using the SimuLED software package from STR. In particular, the relationship of the injection efficiency, on the number of quantum wells, and bias voltage was analyzed in detail. LED devices based on an optimized seven well MQW structure were fabricated and measured. The results confirm the theoretical predictions and indicate that MQW LEDs can have an output power 2 to 3 times higher than LEDs with a homojunction active region.

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TABLE I
Sequence of layers for the mid-infrared AlInSb bulk epi-grown structure from top to substrate (homojunction)

Layer thickness (nm)	Material	x	Type	Conc. (cm^{-3})
500	Al(x)In(1-x)Sb	0.05	p	7E+17
20	Al(x)In(1-x)Sb	0.2	p	7E+17
1000	Al(x)In(1-x)Sb	0.05	i(n)	9E15
3000	Al(x)In(1-x)Sb	0.05	n	7E17
300	GaSb			
	GaAs Substrate			

TABLE II
Sequence of layers for the mid-infrared AlInSb bulk epi-grown structure from top to substrate (DH)

Layer thickness (nm)	Material	x	Type	Conc. (cm^{-3})
500	Al(x)In(1-x)Sb	0.09	p	7E+17
20	Al(x)In(1-x)Sb	0.2	p	7E+17
1000	Al(x)In(1-x)Sb	0.05	i(n)	9E15
3000	Al(x)In(1-x)Sb	0.09	n	7E17
300	GaSb			
	GaAs Substrate			

II. EPI STRUCTURES AND SIMULATIONS

The conventional homojunction bulk structure is shown in Table 1. The epi-layers consist of a GaSb buffer layer, a 3-µm n-type doping layer, followed by a 1-µm undoped active layer and a 0.5-µm p-type layer. A 20-nm p-type $Al_{0.2}In_{0.8}Sb$ barrier layer was grown between the p−layer and active layer in order to reduce carrier leakage [3, 4]. The investigated DH bulk structure is shown in Table 2. Only the Al content in the p-type and n-type layers was increased from 0.05 to 0.09 to form the heterojunction barriers. For the MQW structures, we used doped $Al_{0.2}In_{0.8}Sb$ as the confinement layers and the designed MQW consisted of three to twenty 15-nm $Ga_xIn_{1-x}Sb$ quantum wells/20-nm $Al_yGa_zIn_{1-y-z}Sb$ quantum barriers instead of bulk material as the active region. The center

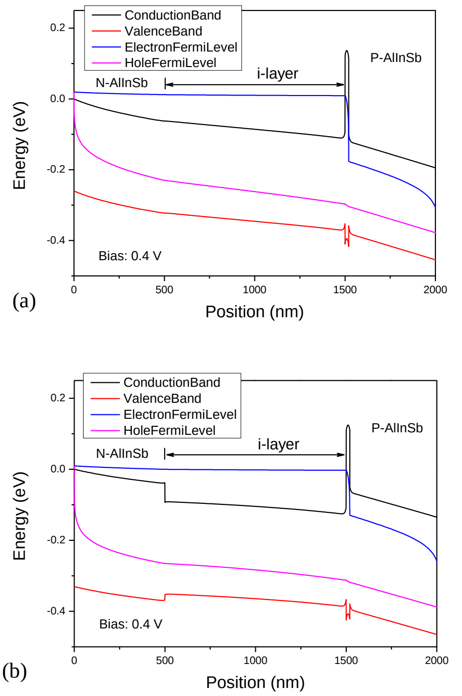

Fig. 1. Energy-band diagrams of mid-infrared AlInSb bulk structures: (a) homojunction; (b) DH.

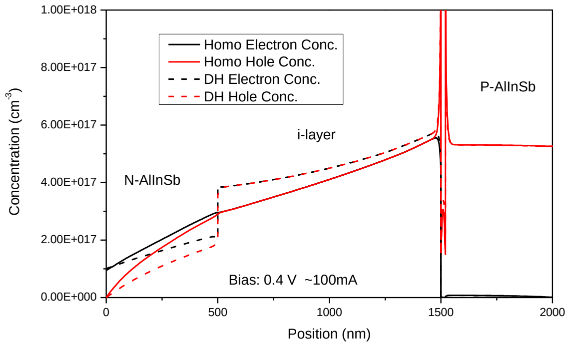

Fig. 2. Carrier concentration distribution of mid-infrared AlInSb bulk structures: homojunction vs. DH.

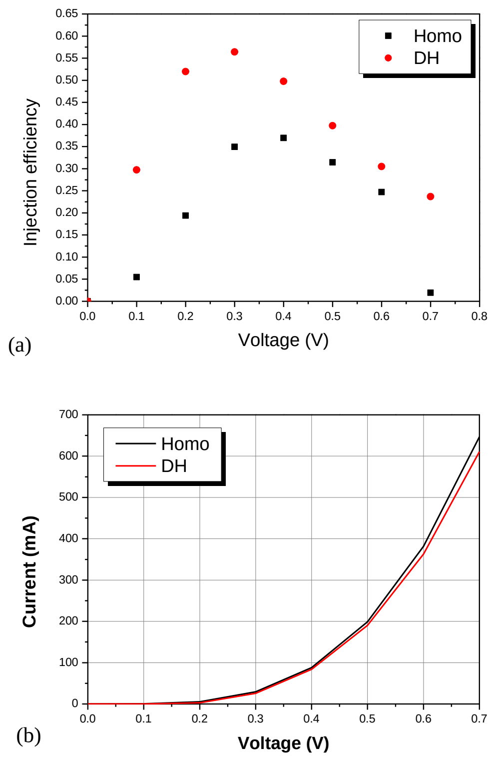

Fig. 3. (a) Simulated injection efficiency as a function of bias voltage, (b) I-V curves of mid-infrared AlInSb bulk structures: homojunction vs. DH.

emission wavelength for all structures was designed at around 4.3 µm for the absorption and detection of carbon dioxide.

The band diagrams of the conventional homojunction and the DH bulk structures under the bias voltage of 0.4 V are shown in Fig. 1 (a) and (b), respectively. As expected, for larger barriers, a corresponding improvement in the carrier confinement can be seen from the DH band diagram. Fig. 2 shows the carrier concentration distribution for the homojunction and the DH bulk structures under a bias voltage of 0.4 V. The carrier concentrations in DH are higher than that in homojunction active region, which indicates a reduced carrier leakage, especially at the n-type AlInSb side. A further advantage is that a more uniform carrier concentration distribution can be obtained in the DH active region. Fig. 3(a) compares the simulated injection efficiency as a function of the bias voltage for the mid-infrared AlInSb bulk structures with homojunction and DH active regions. The injection efficiency of the DH active region is much higher than that of the homojunction active region. The I-V characteristics of Fig. 3(b) indicate that the inclusion of a DH active region does not change the diode electrical performance.

Figure 4 shows the simulated injection efficiency as a function of bias voltage and the I-V characteristics of mid-infrared AlInSb devices with MQW structures. The quantum well numbers are 3, 5, 7, 10, 15, and 20. As expected, the injection efficiency increases with increasing quantum well number and the injection efficiency decreases with increasing bias voltage. It is possible to further enhance the carrier confinement by increasing the energy band offset of the barriers, thereby further improving the injection efficiency.

III. Experimental Results of MQW LEDs

An AlInSb epitaxial wafer with a seven wells MQW structure was grown and the AlInSb LEDs were fabricated following the fabrication procedure described in [1]. Fig. 5 (a) compares the EL spectra of the mid-infrared AlInSb LEDs with MQW and with homojunction active regions obtained with pulsed current of 100 mA (1-kHz frequency and 10% duty cycle). A three-times improvement in the peak intensity can be observed from the MQW active region under the same operating current conditions. The spectra of Fig. 5 (b) show

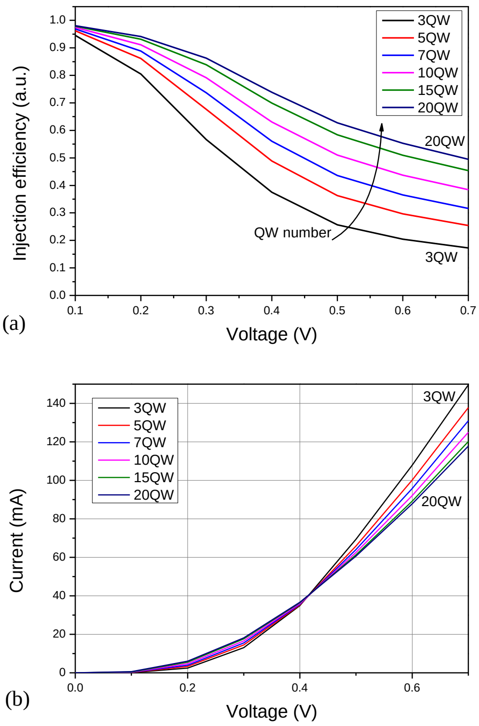

Fig. 4. (a) Simulated injection efficiency as a function of bias voltage, (b) I-V curves of mid-infrared AlInSb with MQW structures.

that a similar peak intensity is emitted when an electrical power of ~1 mW and ~2-mW are injected in the MQW LED and the homojunction LED, respectively. The reason for which the improvement in wall-plug efficiency is not as pronounced as that measured for the EL intensity is due to the higher contact resistivity of the MQW epilayer.

IV. Conclusion

Mid-infrared AlInSb LEDs based on DH and MQW active regions have been investigated. Simulation results show that a better carrier confinement and a more uniform carrier distribution in active region can be attained by including DH and MQW active regions in the epilayer design. The experimental results indicate that a DH-MQW design can provide a three-times increase in output power and a two-times increase in the wall-plug efficiency compared to a homojunction design.

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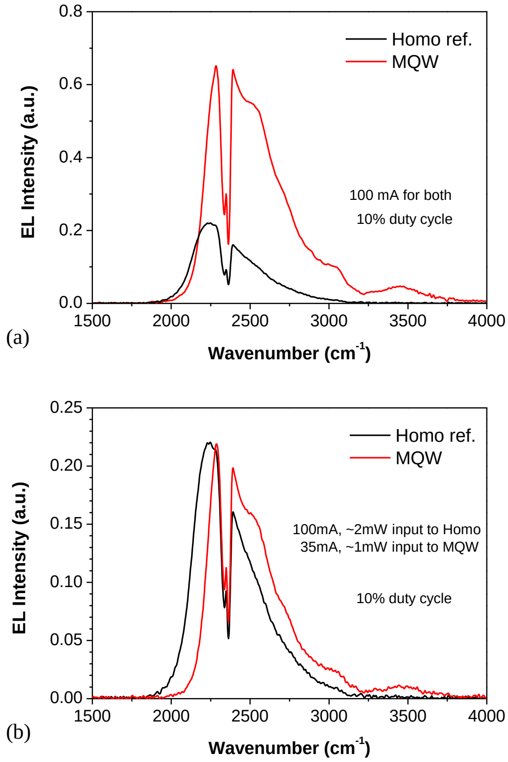

Fig. 5. Comparison of EL spectra of mid-infrared AlInSb LEDs with homojunction (as a reference) and MQW active regions, (a) under the same 100-mA pump current conditions; (b) with the same peak intensity. The dip in the spectra at around 2350 cm^{-1} is due to CO_2 absorption in the lab.

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