Investigation of mid-infrared AlInSb LEDs with an n-i-p structure

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Abstract-We report on the investigation on mid-infrared AlInSb LEDs with an n-i-p structure. Compared to the conventional AlInSb LEDs with a p-i-n structure, a better current spreading corresponding to a uniform current distribution in the active region is expected in the n-i-p structure because of a high electron mobility in the n-type AlInSb material. The output optical power of laterally injected LEDs were investigated as a function of the device geometry by COMSOL simulations and confirmed by experimental results.

Index Terms—p-i-n diodes, Electroluminescence (EL), Light emitting diodes (LEDs), Mid-infrared

I. Introduction

Because of the issues of current crowding and light blocking by the contact electrode in conventional AlInSb LEDs with a p-i-n structure [1] (that is p-type top emitting layer) [2], it is difficult to further improve the electro-to-optical conversion efficiency of the LEDs by keeping the basic device structure and mounting technique unchanged. The very high electron mobility (1.55 x 10^4 $cm^2/(V\cdot s)$ from our Hall measurement) in n-type $Al_{0.05}In_{0.95}Sb$, approximately 35-times higher than hole mobility (440 $cm^2/(V\cdot s)$) in p-type $Al_{0.05}In_{0.95}Sb$, leads to very low lateral spreading resistivity in the n-type AlInSb material. Therefore the use of an n-type AlInSb as the current spreading layer appears as a promising approach to improve the current distribution in the LED devices' active region. This only requires swapping the p- and n-doping sequence during the material epitaxial growth and does not need other growth conditions or device configurations to be changed.

In this work, we report on the design and epitaxial growth of an AlInSb with an n-i-p structure. The current spreading and distribution in the n-i-p structures was simulated using the semiconductor module of COMSOL multiphysics [3] and the results were compared with measurements on LEDs with different size. Both the simulation and experimental results show that AlInSb LEDs with an n-i-p structure in combination with a small chip size exhibit higher optical extraction.

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TABLE I
Mid-infrared AlInSb epi-grown structure (n-i-p structure)

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

TABLE II
Mid-infrared AlInSb epi-grown structure (p-i-n structure)

nm	Material	x	Type	Conc.
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			

II. Epi Structures and Simulations

The samples investigated in this work were grown on semi-insulating GaAs substrates by molecular beam epitaxy (MBE). The layer structures of the LED epi-layers with an n-i-p and a p-i-n structure are shown in Table I and Table II, respectively. The epi-layers consist of a GaSb buffer layer, a 3-μm lower doping layer, followed by a 1-μm undoped active layer and a 0.5-μm current spreading and contact 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 carriers' leakage [2, 4]. The doping concentration is ~$7\times10^{17}/cm^3$ for both n-type and p-type layers and the unintentional background doping concentration in the active region is ~$9\times10^{15}/cm^3$. Tellurium and beryllium are used for n-type and p-type dopants, respectively. The center emission wavelength was adjusted at around 4.3 μm through changing Al content in the active region for the absorption and detection of carbon dioxide.

The LED device structure is usually realized with a coplanar electrode configuration in order to avoid the high resistance caused by the high density of defects at the interface between the GaAs substrate and GaSb buffer layer.

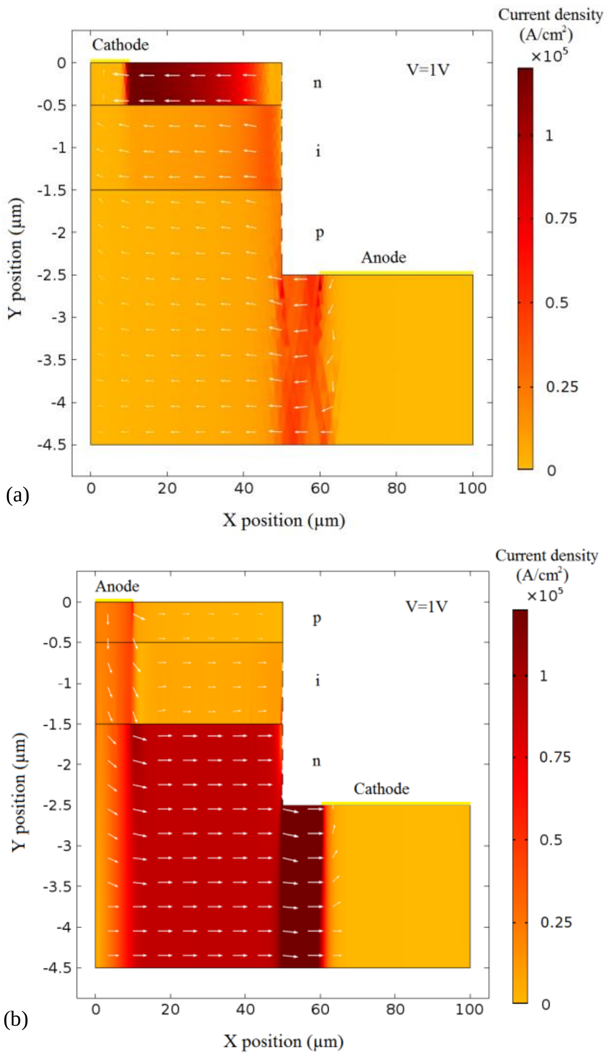

Fig. 1. Geometry and vector field of the current density of mid-infrared AlInSb LEDs: (a) n-i-p structure; (b) p-i-n structure.

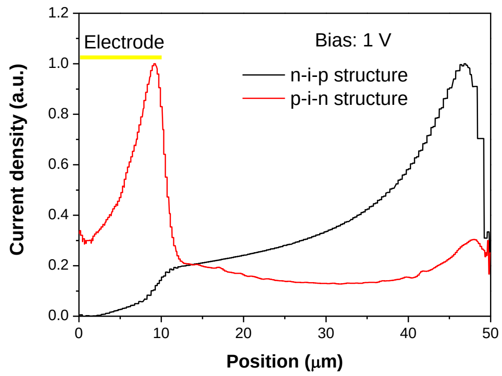

Fig. 2. Comparison of current density distribution of mid-infrared AlInSb LEDs: n-i-p structure vs. p-i-n structure.

A 2-D device model with coplanar electrodes as shown in Fig. 1 was built using the semiconductor module of COMSOL multiphysics. Because the geometry is symmetrical, only half of the device was simulated. The main material parameters,

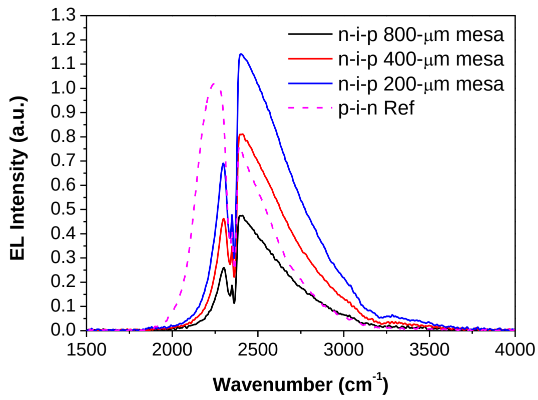

Fig. 3. Comparison of EL spectra of mid-infrared n-i-p AlInSb LEDs with different mesa sizes under the same pump current conditions. The EL spectrum of a conventional p-i-n AlInSb LED under the same pump current condition is also included as a reference. The dip in the spectra at around 2350 cm^{-1} is due to CO_2 absorption in the lab.

such as carrier concentration and mobility were determined by Hall measurements. In Fig.1, the simulated current density distributions in a 100-μm mesa were plotted by vector mode on both the n-i-p and p-i-n structure. A clearer illustration and comparison of current density distributions for the two devices is shown in Fig. 2. As expected, a more uniform current distribution in the active region without electrode shadowing is found for the device with an n-i-p structure.

III. RESULTS AND DISCUSSION

N-i-p AlInSb LEDs with different mesa sizes (200 μm, 400 μm, and 800 μm) were fabricated and the measured Electro-Luminescence (EL) spectra together with a reference EL spectrum of a p-i-n AlInSb LED (800-μm mesa) are shown in Fig. 3. The pulsed current of 100 mA (1-kHz frequency and 10% duty cycle) was applied to all the LEDs. The spectral shift between the p-i-n and the n-i-p structure in Fig. 3 is due to a small change of Al composition during MBE growth and it can be easily adjusted by optimising growth parameters. As expected, the output optical power of the n-i-p AlInSb LEDs strongly depends on the LED mesa size because of the lateral injection configuration. However, this trend is not observed in the p-i-n AlInSb LEDs, i.e., there is no pronounced difference between the LED with a 400-μm and an 800-μm mesa. The current density distributions in the three n-i-p AlInSb LEDs with different mesa sizes were simulated and the results are shown in Fig. 4. We kept the same n-electrode width of 40 μm for all three geometries. With increasing mesa size, the current crowding became progressively worse close to the sidewall of the mesa which may lead to the efficiency droop in the n-i-p LEDs with a larger mesa. On the contrary, the LED with a small mesa has a relatively uniform current distribution and the EL intensity is higher than the standard reference LED with a p-i-n structure. Compared to AlInSb LEDs with a p-i-n structure, the presented n-i-p structure will be more suitable for small size devices (e.g.

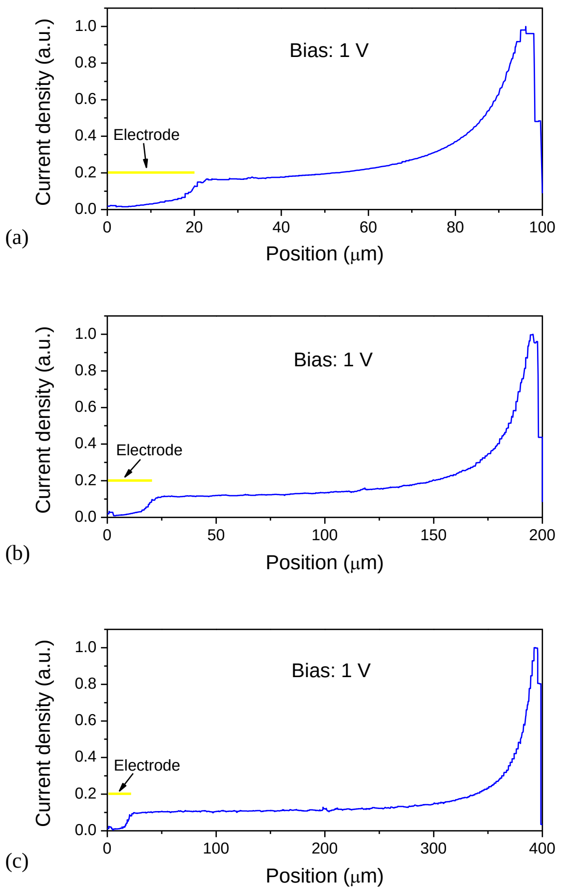

Fig. 4. Comparison of current density distribution of mid-infrared AlInSb LEDs with n-i-p structure: (a) 200-μm mesa; (b) 400-μm mesa; (c) 800-μm mesa.

with a mesa size of a few tens microns) such as micron sensors or multiple diodes arrays etc.

IV. Summary

We investigate the mid-infrared AlInSb LEDs with an n-i-p structure. Simulation and experimental results indicate that the n-i-p structure in combination with a small chip size can be promising for efficient optical extraction and output.

Acknowledgment

Y.D. would like to thank the technical staff of the James Watt Nanofabrication Centre at the University of Glasgow.

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