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Performance of Various LEDs for Gas Sensor Instrumentation in Mid-infrared (2-5µm) Spectral Region

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ABSTRACT
In this paper, performance studies have been carried out for mid-infrared (MIR) homojunction LED, single heterojunction LED (SH-LED) and double heterojunction LED (DH-LED) based on narrow bandgap semiconductors. The various trial structures have been modeled and simulated using an analytical technique, numerical model and device simulation package ATLAS™ for exploring their possible use in toxic and pollutant gas detection systems in the mid-infrared spectral region. The effect of minority carrier concentration on the lifetime of the carrier has been modeled to explain the saturation of LEDs output at high bias current. The results obtained by simulation techniques for various mid-infrared LEDs have been contrasted with the reported experimental results and found to be in good agreement.

Keywords: Gas-sensor, Instrumentation, LEDs, Pollution, Mid-infrared

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I. INTRODUCTION

The mid-infrared (MIR) region of the infrared spectrum, contains the fundamental fingerprint absorption bands of many pollutants combustible/toxic and liquids such as hydrocarbons like NH_3 (2.3µm), H_2S (2.7 µm), CH_4 (3.3µm), CO2 (4.2 µm) and CO (4.6 µm) [1]. They all require accurate in situ multi-component monitoring in a variety of different situations like oil rigs, coal mines, landfill sites, car exhaust and many more. The mid-infrared region also provides a unique fingerprint with strong absorption bands for the drug intermediates, pharmaceuticals, narcotics and bio-chemicals allowing highly sensitive and selective detection. MIR is thus favorite for the development of sensitive sensor instrumentation in the fields of environmental monitoring, bio-medicine, industrial process control and health and safety.

The sources for the mid-infrared spectral region are essentially being the Light-emitting diode (LED) and injection laser diode (ILD) based on semiconductor materials. In order to obtain emission beyond 2 µm wavelength, the bandgap of the material must be lower than 0.62 eV. The semiconductor having bandgap equivalent to the cut-off wavelength over 2 µm are termed as narrow bandgap semiconductors [2,3]. The room temperature continuous operation of MIR LEDs is limited by non-radiative recombination such as Shockley-Read-Hall (SRH) and Auger recombination process, which are the dominating recombination mechanisms for narrow bandgap semiconductors. Several narrow bandgap material systems based on IV-VI Rock Salt (PbS, PbSe, $Pb_{1-x}Sn_xTe$), II-VI ($Hg_{1-x}Cd_xTe$), III-V ($In_{1-x}Ga_xAs$, InAs, InSb, $InAs_{1-x}Sb_x$, $InAs_xSb_yP_{1-x-y}$) have been studied for mid-infrared sources. These material systems opened new avenues for tailoring energy bandgap of semiconductors to meet custom specified applications. While IV-VI Rock Salts and II-VI material systems suffer from the poor mechanical and thermal properties, a number of III-V semiconductor alloy benefited from stronger covalent bonding and advanced growth and processing technologies, have been investigated for the fabrication of MIR sources. The other advantages of the III-V binary and ternary alloys over the other materials systems include high electron and hole mobility, availability of high quality and low-cost substrate, low dielectric constant (≈11.5), low room temperature self-diffusion coefficient (≈ $5.2x10^{-20}m^2$/sec) and fairly weak dependence of the band edge on composition [4,5].

Based upon the favorable properties, it is proposed to undertake the critical theoretical investigations concerning modeling and analysis of different mid-infrared sources based on InAs, InAsSb, and InAsSbP alloy semiconductor. A comparative modest approach has been adopted to explore the potential of III-V narrow bandgap semiconductor for the MIR sources operating at room temperature for several MIR applications including pollutant/ toxic gas detection systems.

II. MODELS FOR MID-INFRARED HOMOJUNCTION LED

The Analytical and ATLAS simulation models of mid-infrared homojunction p-i-n light-emitting diode based on p^+-$InAs_{0.91}Sb_{0.09}$/ n^0-$InAs_{0.91}Sb_{0.09}$/ n^+-$InAs_{0.91}Sb_{0.09}$ materials system have been formulated and reported by the author [6]. The various electro-optic properties of the structure have been estimated analytically and using commercially available device simulation software ATLAS™ [7]. The results of both the models have been compared/contrasted with the reported experimental results. The optical power of the homojunction LED calculated using the analytical model is found to match with that of the experimentally measured values, especially at low bias currents.

The analytical model estimates a little higher optical output than the experimentally measured output. This may be attributed to the fact that at higher bias current the minority carrier lifetime may depend much more strongly on the injected carrier density than assumed in our analytical model. However, this may be also due to trap-assisted recombination which has not been considered in the analytical model. In the case of the ATLAS simulated model, however, the results have been found to be in good agreement with the reported experimental results even at the higher bias.

III. MODELS FOR MID-INFRARED SINGLE HETEROJUNCTION LED

A physics-based closed analytical model of MIR single heterojunction LED (SH-LED) based on P^+-$InAs_{0.36}Sb_{0.20}P_{0.44}$/ n^0-InAs/ n^+-InAs material system for operation in 2.4–3.5 μm spectral range at room temperature has been developed and the results are compared with the reported experimental data. Also, the numerical model of the same structure using a commercially available device simulation package ATLAS™ has been carried out by the author [8]. The simulation results have also been compared with reported analytical and experimental results and found to be in good agreement [9]. The analytical model gives slightly less value of the output power at high bias current as compared to the reported experimental results. However, the ATLAS simulation results show a better agreement with experimental data even at higher bias current [9].

IV. MODELS FOR MID-INFRARED DOUBLE HETEROJUNCTION LED

The analytical and numerical simulation models of a MIR double heterojunction light-emitting diode (DH-LED) based on P^+-$InAs_{0.48}Sb_{0.22}P_{0.30}$/ n^0-$InAs_{0.89}Sb_{0.11}$/ N^--$InAs_{0.48}Sb_{0.22}P_{0.30}$ material system have on by Sanjeev et al. [10, 11]. The results in respect of output power versus bias current of both the models have been compared separately with the reported experimental results. Whereas the results of numerical simulation match fairly well with the experimental one, the analytical results showed a little deviation especially at the high bias current. This may be because of the fact that we have not considered the effect of superluminsence phenomenon occurring in DH-LED especially at higher bias current.

V. RESULTS AND DISCUSSION

The performance of all mid-infrared LEDs have been evaluated under high injection condition and it is found to be dependent on the injected carrier density. Fig.1 shows the variation of Auger and a radiative lifetime of the carriers with the excess injected carriers. It is seen that the lifetime of carriers decreases drastically with the increase in the excess injected carrier beyond $10^{24}/m^3$. It is also observed that Auger recombination lifetime decreases much faster than other non-radiative recombination lifetime and becomes dominating as we increase the injected carrier beyond $10^{25}/m^3$. Hence, it is dominating non-radiative recombination under high injection condition which affects the output power of the MIR LEDs. The performance data of various MIR LEDs trial structures with respect to typical optical output versus bias current have shown in Fig. 2. Here, the output power of various LEDs is normalized with respect to the power of the DH-LED, so as to critically compare the relative variation in output power for the given bias current. It is clear from the graph that output power for the homojunction is the smallest for a given value of bias current. The SH-LED is having more output power with the same input bias current owing to the better optical and carrier confinement in the single hetero-structure. In the case of DH-LED, the relative optical power is maximum due to the more effective carrier and optical confinement in the double hetero-structure. However, it has been seen that the dependence of carrier lifetime adversely affects the power output in the case of DH-LED, which leads to the phenomenon of saturation in the DH-LED, especially at high bias current. However, as the number of injected carrier concentration is low in the case of SH-LED and Homojunction LED, the output power saturation occurs at higher bias current as compared to the DH-LED.

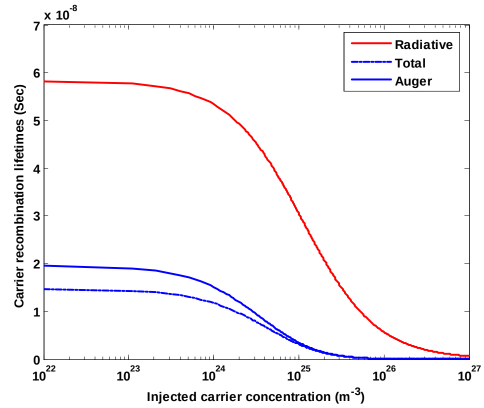

Fig. 1. Effect of injected carrier concentration with the carrier lifetime.

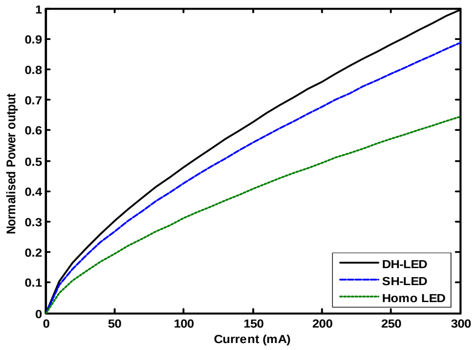

Fig. 2 The normalized simulated output power of Homojunction LED, SH-LED and DH-LED.

The simulated current-voltage characteristics of homojunction LED, SH-LED and DH-LED have been summarised in Table 1. It is evident from the table that current-voltage characteristics for the same value of voltage the current values are increasing as we go from homojunction to DH-LED. Table 2 illustrate individually normalized output power with the input bias current for homojunction, SH-LED and DH-LED. The individual normalized values of the output power again confirm the results shown in Fig.2. The better output power for the given value of the bias current in the case of DH-LED again a result of better confinement of carriers and optical signal in the double heterojunctions.

Table 1. The current-voltage characteristics of various MIR LEDs

Typical Values of Voltage (V)	Current (A) for					
	Homojunction LED		SH-LED		DH-LED	
	Analytical Model	ATLAS Model	Analytical Model	ATLAS Model	Numerical Model	ATLAS Model
0.10	$4.0x10^{-6}$	$3.0x10^{-6}$	$5.0x10^{-7}$	$4.9x10^{-7}$	$5.9x10^{-8}$	$5.0x10^{-8}$
0.25	$3.5x10^{-3}$	$3.4x10^{-3}$	$1.2x10^{-3}$	$1.2x10^{-3}$	$1.0x10^{-3}$	$1.1x10^{-3}$

Table 2. The Output power versus bias current values of Analytical model, ATLAS model, numerical model and reported experimental data for various MIR LEDs structures

Typical Values of Bias Current (mA)	Normalised Output Power for								
	Homojunction LED			SH-LED			DH-LED		
	Analytical Model	ATLAS Model	Reported Exp.	Analytical Model	ATLAS Model	Reported Exp.	Analytical Model	Numerical Model	Reported Exp.
100.0	0.33	0.32	0.30	0.480	0.499	0.479	0.64	0.69	0.75
200.0	0.53	0.53	0.53	0.761	0.782	0.800	0.81	0.85	0.79

VI. CONCLUSION:

The analytical models help one to have a better understanding of various mechanisms involved in the operation of the devices. On the other hand, numerical simulations carried out by using commercial software tools to provide accurate prediction of performances of complex devices under various operating conditions. As the numerical simulations are based on minimum assumptions, the results are in better agreement with the experimentally measured data. The study reveals that a high level of carrier injection results in a reduction in the effective lifetime of the carriers which in turn causes the output power to saturate at higher bias current. It is also found that the quantum efficiency of the MIR source significantly affected by the non-radiative recombination process including surface recombination. In order to improve the performance of room temperature mid-infrared LEDs based on narrow bandgap semiconductors, it is necessary to suppress both Auger and SRH recombination. SRH recombination can be greatly reduced by improving the processing of the device whereas one has to modify the device structure suitably using the concept of bandgap engineering in order to reduce Auger recombination at room temperature and under high injection. The model developed here would provide useful design guidelines for the experimentalists for developing new device prototypes.

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