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Self-Heating Effects in a Silicon Carbide Polymers (6H-SiC and 3C-SiC) Semiconductor Laser

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In this paper, we present the effects of self-heating on the characteristics of a silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser. The device employs 3C-SiC quantum well, which is sandwiched between two layers of 6H-SiC as cladding regions that can be interpreted in terms of a type-II heterostructure character and a built-in electric field due to the pyroelectricity of 6H using a numerical simulator. This paper provides key results of the device characteristics upon lattice temperature heating, including the output power *versus* electrical bias and the DC I-V.

Key Words: Self-heating effects, 6H-SiC and 3C-SiC, Semiconductor laser.

INTRODUCTION

During the past decades, silicon carbide (SiC) has been praised as a promising semiconductor material for high power, high-frequency and high-temperature electronics and optoelectronic devices, where the existing Si or GaAs technology cannot provide any satisfactory performance. This intensive research effort resulted in the commercialization of the first silicon carbide-based devices in year 2001 namely, high power Schottky diodes[1]. Properties such as the large breakdown electric field strength, large saturated electron drift velocity, small dielectric constant, reasonably high electron mobility and high thermal conductivity make Sic an attractive candidate for fabricating power devices with reduced power losses and die size[2].

Silicon carbide has many stable polytypes, including cubic zinc-blende, hexagonal and rhombohedral polytypes. In the cubic zinc-blende structure, labeled as 3C-SiC or β-SiC, Si and C occupy ordered sites in a diamond framework. In hexagonal polytypes nH-SiC and rhombohedral polytypes n R-SiC, generally referred to as αη-SiC, n Si-C bilayers consisting of C and Si layers stack in the primitive unit cell. The lattice structures of the 3C-SiC and 6H-SiC phases, which are most important for this paper, are presented in Fig. 1[3].

Lattice heat is generated whenever physical processes transfer energy to the crystal lattice. According to differences in transfer mechanisms, heat sources can be separated into Joule heat, electron-hole recombination heat, Peltier-Thomson heat and heat from optical absorption. Self-heating often limits the performance of optoelectronic devices. Heat is generated when carriers transfer part of their energy to the crystal lattice. In consequence, the thermal energy of the lattice rises, which is measured as an increase in its temperature[4].

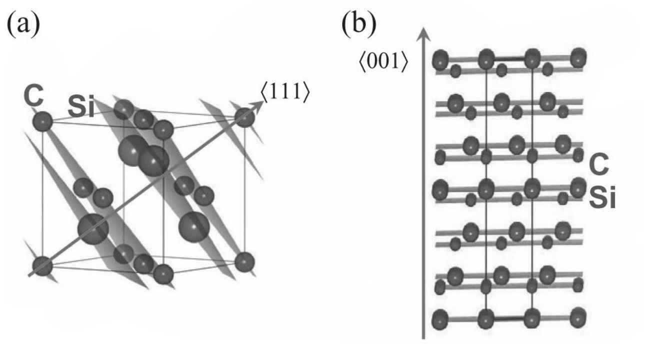

Fig. 1. (a) Unit cell of cubic 3C-SiC. (b) Four unit cells of hexagonal 6H-SiC

In this paper, we studied the self-heating effects on the characteristics of a silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser.

EXPERIMENTAL

In modeling edge emitting laser, we considered the electrical, optical and thermal interaction during laser performance. Thus base of simulation is to solve Poisson and continuity equations for electrons and holes[5]. Poisson's equation is defined by:

$$\nabla.(\varepsilon\nabla\psi) = \rho \qquad (1)$$

where, ψ is electrostatic potential, ρ is local charge density and ε is local permittivity. The continuity equations of electron and hole are given by[4]:

$$\frac{dn}{dt} = G_n - R_n + \frac{1}{q}\nabla.j_n \qquad (2)$$

$$\frac{dp}{dt} = G_p - R_p + \frac{1}{q}\nabla.j_p \qquad (3)$$

where, n and p are the electron and hole concentration, J_n and J_p are the electron and hole current densities, G_n and G_p are the generation rates for electrons and holes, R_n and R_p are the recombination rates and q is the magnitude of electron charge.

The fundamental semiconductor equations (1)-(3) are solved self-consistently together with Helmholtz and the photon rate equations. The applied technique for solution of Helmholtz equation is based on improved effective index model[6], which shows accuracy for great portion of preliminary problems. This model is good adapted to simulation of laser structures and it is often called effective frequency method[7].

Two-dimensional Helmholtz equation is solved to determine the transverse optical field profile and it is given by[5]:

$$\nabla^2 E(r,z,\varphi) + \frac{\omega_0}{c^2}\varepsilon(r,z,\varphi,\omega)E(r,z,\varphi) = 0 \qquad (4)$$

where ω is the frequency, $\varepsilon(r, z, \varphi, \omega)$ is the complex dielectric permittivity, $E(r, z, \varphi)$ is the optical electric field and c is the speed of light in vacuum. The light power equation relates electrical and optical models. The photon rate equation is given by[5]:

$$\frac{dS_m}{dt} = \left(\frac{c}{N_{eff}}G_m - \frac{1}{\tau_{ph_m}} - \frac{cL}{N_{eff}}\right)S_m + R_{sp_m} \qquad (5)$$

where, S_m is the photon number, G_m is the modal gain, R_{spm} is the modal spontaneous emission rate, L represents the losses in the laser, N_{eff} is the group effective refractive index, τ_{phm} is the modal photon lifetime and c is the speed of light in vacuum. The heat flow equation has the form[5]:

$$C\frac{\partial T_L}{\partial t} = \nabla(\kappa\nabla T_L) + H \qquad (6)$$

where, C is the heat capacitance per unit volume, κ is the thermal conductivity, H is the generation, T_L is the local lattice temperature and H is the heat generation term.

Equations (1)-(6) provide an approach that can account for the mutual dependence of electrical, thermal, optical and elements of heat sources. In this paper, we employ numerical-based simulation software to analyze the self-heating effects on the characteristics of a silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser[5].

Fig. 2 shows the schematic design of 0.83 μm strained quantum-well laser diode device. The lasers used in this work were separate-confinement quantum-well lasers with a single strained 3C-SiC quantum well, 10 nm wide, located in a lattice-matched waveguide core and cladding region of 6H-SiC with wide of layers 95 nm and 1500 nm respectively.

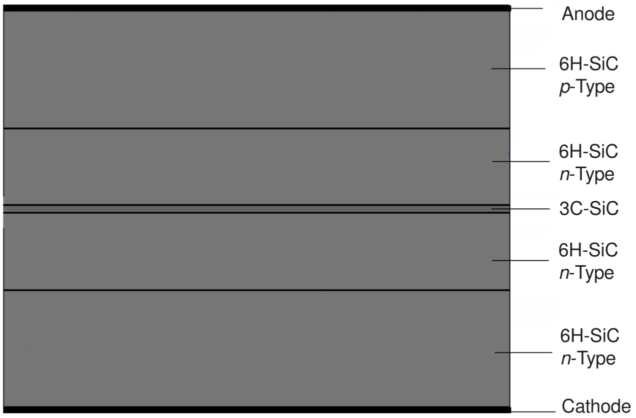

Fig. 2. Schematic structure of the laser device

RESULTS AND DISCUSSION

Heat loss from the modeled laser device was specified using thermal contacts at the top electrode, bottom electrode and the device sidewall. The thermal contacts define thermal conductivities to simulate heat loss from radiation *via* exposed surfaces or conduction through the semiconducting material to a heatsink.

The thermal contact temperature was varied from 300 K until 350 K and its effect on the P-V and I-V curves are shown in Figs. 3 and 4 respectively. The P-V and I-V curves show that for a given voltage value, increment in lattice temperature decreases the output power and current; especially at higher voltages. This decrement should be mainly due to an increase in dark carrier recombination within the device. However, the small change in lattice temperature does not affect the optical gain.

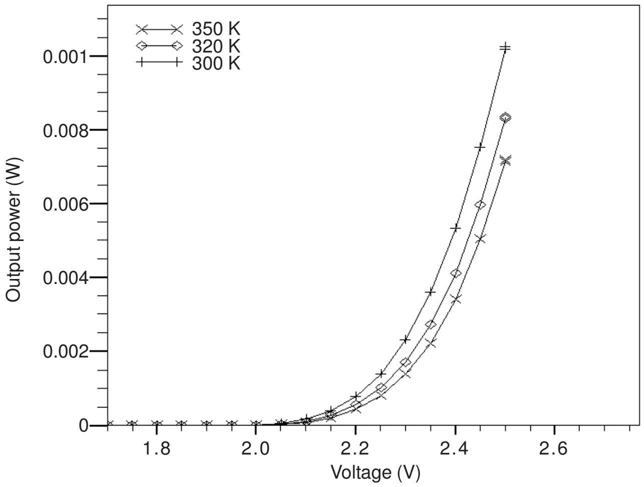

Fig. 3. Temperature effect on the P-V curve

Figs. 3 and 4 show the slight increment in the threshold current when the lattice temperature is increased. This increment should be mainly due to broadening of the gain spectrum and the overflow of carriers. In other words, the thermal rollover effect could be caused by leakage currents or dark recombination processes because these are the temperature dependence factors.

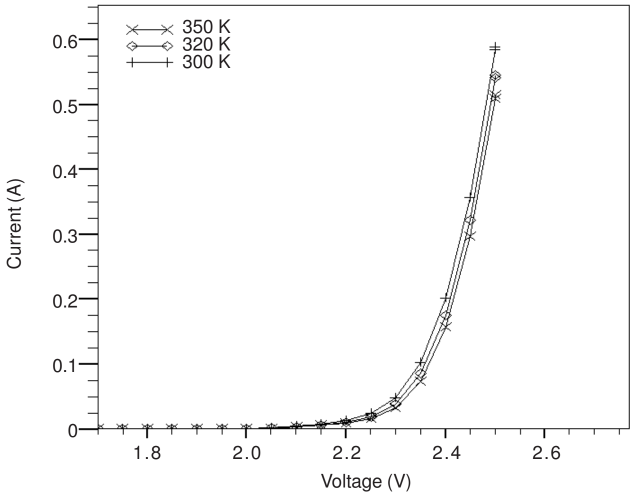

Fig. 4. Temperature effect on the I-V curve

Conclusion

In this paper, we have modeled the self- heating effects in a silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser operating in the 830nm wavelength regime. We have studied the effects of lattice temperature increment on the device characteristics and could show the temperature variation within the device due to self-heating effects. In summary, lattice temperature increment decreases the output power and current by lowering the device's thermal conductivity.

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