Asian Journal of Chemistry; Vol. 24, No. 7 (2012), 3123-3125

ASIAN JOURNAL OF CHEMISTRY

www.asianjournalofchemistry.co.in

Effects of Lattice Temperature on the Various Elements of Heat Sources in Silicon Carbide Polymers (6H-SiC and 3C-SiC) Semiconductor Laser

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(*Received*: 18 July 2011; *Accepted*: 18 February 2012) AJC-11080

In present paper, the various elements of heat sources within a silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser device were analyzed upon the increment of lattice temperature. 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. The thermal resistance used to model the electrical contacts causes an approximate temperature rise by 29.3 K above the ambient temperature (300 K) at a bias of 2.5 V and a 17.094 % decrease from 1.3432e10 W/cm^3 to 1.1136e10 W/cm^3 in the total heat power is observed with temperature increment.

Key Words: Lattice temperature, Heat sources, Silicon carbide polymers, Semiconductor laser.

INTRODUCTION

The use of strained quantum wells (QW's) to improve the performance of semiconductor lasers was suggested by Adams[1] and Yablonovich and Kane[2] and strained wells are now usually used in such different material systems as In GaAs-GaAs, GaInP-AlGaInP and InGaN-GaN. Strained quantum well lasers are used for a number of technically important applications, but there has been little work reporting the methods that finally limit their performance at high strain.

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 SiC-based devices in year 2001 namely, high power Schottky diodes[3]. 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[4].

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[5].

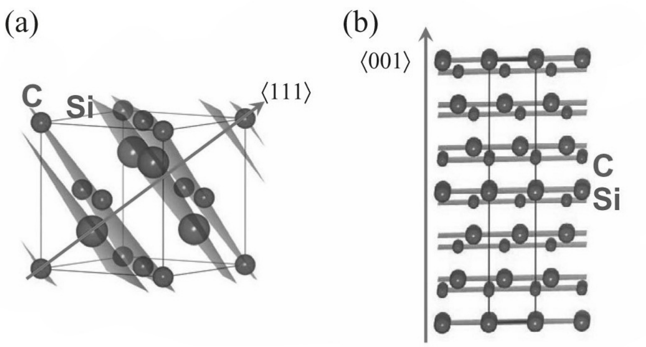

Fig. 1. (a) Unit cell of cubic 3C-SiC. (b) Four unit cells of hexagonal 6H-SiC

In this paper, the lattice temperature in a silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser, was varied between 300 K until 350 K and its effects on the various elements of heat sources of the device was analyzed. We give details of the laser design and describe their effects on the various elements of heat sources and briefly describe the photoluminescence data from present structure. Next the obtained numerical results are presented. Finally, the conclusions provide common guidelines for designing performance of edge emitting laser.

EXPERIMENTAL

In modeling edge emitting laser, we must consider the electrical, optical and thermal interaction during laser performance. Thus base of simulation is to solve Poisson and continuity equations for electrons and holes[6]. Poisson's equation is defined by:

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

where, ψ is electrostatic potential, ∇ is local charge density and ε is local permittivity. The continuity equations of electron and hole are given by[7]:

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

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

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[8], which shows accuracy for great portion of preliminary problems. This model is very good adapted to simulation of laser structures and it is often called effective frequency method[9].

Two-dimensional Helmholtz equation is solved to determine the transverse optical field profile and it is given by[6]:

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

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[6]:

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

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[6]:

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

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.

The heat generation equation has the form[6]:

$$H = [\frac{\left|\overrightarrow{J_n}\right|^2}{q\mu_n n} + \frac{\left|\overrightarrow{J_p}\right|^2}{q\mu_p p}] + q(R-G)[\phi_p - \phi_n + T_L(P_p - P_n)] - T_L(\vec{J}_n\nabla P_n + \vec{J}_p\nabla P_p) \quad (7)$$

where: $[\frac{\left|\overrightarrow{J_n}\right|^2}{q\mu_n n} + \frac{\left|\overrightarrow{J_p}\right|^2}{q\mu_p p}]$ is the Joule heating term, $q(R-G)[\phi_p - \phi_n + T_L(P_p - P_n)]$ is the recombination and generation heating and cooling term, $-T_L(\vec{J}_n\nabla P_n + \vec{J}_p\nabla P_p)$ accounts for the Peltier and Thomson effects.

Equations (1)-(7) 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 assist in the device design and optimization[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.

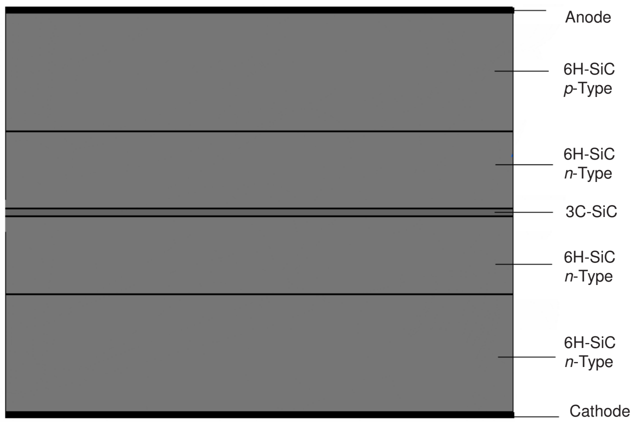

Fig. 2. Schematic structure of the laser device

RESULTS AND DISCUSSION

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, 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[7].

The lattice temperature in a silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser, was varied between 300 K until 350 K and its effects on the various elements of heat sources of the device was analyzed.

Figure 3 shows the total heat power within a vertical cross-section of the device at a bias voltage of 2.5 V. As can be seen from Fig. 3, increasing of the lattice temperature causes the reduction of the total heat power which should be mainly due to lower current density at bias voltage of 2.5 V.

Table-1 shows the maximum of various elements of heat sources upon the lattice temperature, including the total heat power, the Joule heat power, the Peltier-Thomson heat power and the recombination heat power at bias voltage of 2.5 V. As can be seen from Table-1, increment in lattice temperature reduces the heat power values which should be mainly due to lower device's thermal conductivity and current density at bias voltage of 2.5 V. The temperature fluctuation has a direct effect on the gain distribution, causes a peak wavelength shift and is the precursor for various dark current processes within the laser.

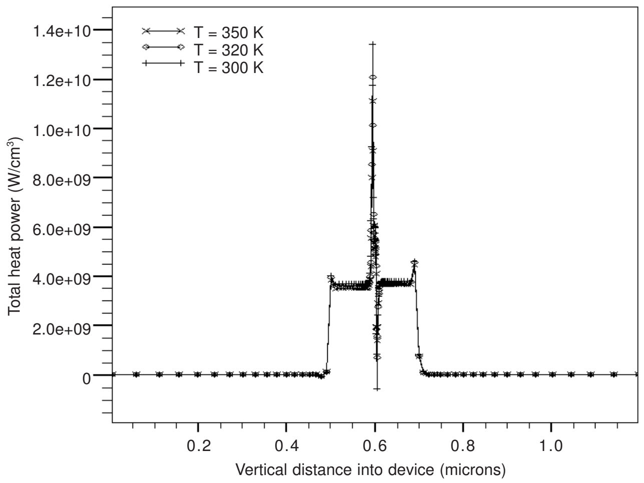

Fig. 3. Effect of lattice temperature on the total heat power within the device

TABLE I
THE MAXIMUM OF VARIOUS ELEMENTS OF HEAT SOURCES UPON THE LATTICE TEMPERATUE, INCLUDING THE TOTAL HEAT POWER, THE JOULE HEAT POWER, THE PELTIER-THOMSON HEAT POWER AND THE RECOMBINATION HEAT POWER AT BIAS VOLTAGE OF 3V

Various elements of heat sources	T=300 K (W/cm^3)	T=320 K (W/cm^3)	T=350 K (W/cm^3)
Maximum total heat power	1.3432e10	1.2081e10	1.1136e10
Maximum joule heat power	1.7946e7	1.4954e7	1.3006e7
Maximum Peltier-thomson heat power	7.6581e9	6.2853e9	5.4123e9
Maximum recombination heat power	6.1184e9	6.0118e9	5.9835e9

Conclusion

In this paper, we have used the silicon carbide polymers (6H-SiC and 3C-SiC) semiconductor laser and the various elements of heat sources were analyzed upon the increment of lattice temperature. In summary, lattice temperature increment decreases the heat power values by lowering the device's thermal conductivity and current density. The maximum heat power of the joule, Peltier-Thomson and recombination are 1.7946e7, 7.6581e9 and 6.1184e9 W/cm^3, respectively at a bias voltage of 2.5 V.

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