

Effective heating in heavily doped semiconductor devices

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A model has been developed to investigate the heat generation processes in semiconductor devices under heavily doped condition. The equilibrium between heat generation and heat dissipation by various mechanisms has been studied. The variations of heat dissipation with the change of carrier concentrations and the heat along the distance from the junction to the bulk have been estimated by numerical analyses. These are shown graphically with the results of an earlier work.

Keywords: Thermal properties, Semiconductor devices, Energy conversion

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1 Introduction

Energy conversion processes in the operation of electronic devices are associated with the generation of heat. To reduce the thermal impact in semiconductor devices, a comprehensive study on heat generation mechanisms must be made. Device analysis can be made by accurate measurement of different device parameters and their operational characteristics.

Various semiconductors respond to heat generation phenomena differently. Investigations on the contributions of different processes to the generation of heat within semiconductor devices have been made by various methods¹⁻⁴ obtained mostly through the solution of Poisson's equation.

A more detailed and elaborate theoretical model for heat generation has been presented by Wachutka⁵⁻⁷, based on thermodynamical approaches. Lindefelt⁸ developed the heat generation processes using mostly Boltzmann's transport equation for the holes and electrons along with the thermal properties of the lattice having a position-dependent band structure and multi-valley band structure.

Zhu *et al.*⁹ introduced an analytical model to simulate accurately both the self-heating effect and its compensation in various characteristics of heterojunction bipolar transistor (HBT). Earlier to this work, theoretical and experimental characterization of self-heating in silicon integrated devices operating at low temperature have been discussed¹⁰. The simulation of hot electron transport and heat generation problem of modulation doped FETs have been presented by the energy relaxation between

carriers and phonons through the use of non-linear charge-control model, rate balance equations and electron-phonon scattering¹¹. When electrons accelerate along the channel, they gain energy from the electric field thereby increasing their drift velocity. This makes the electron temperature higher than that of the lattice. The electrons would release some of their energy by electron-phonon scattering by which there will be generation of heat.

The physical phenomena of various mechanisms have been studied. From these, the effective contributions to the heat generation processes are estimated. A model is developed to deal with the establishment of the equilibrium in the various processes of heat generation and heat dissipation in heavily doped semiconductor devices. The energy balance expressions are consistent with thermodynamic principles. The results of the theoretical model are presented here, the numerical analyses of which are shown graphically along with the numerical computation made from an earlier model⁸.

2 Effective Heat Generation in Semiconductor Devices

The contributions towards effective heat generation in semiconductor devices will be systematically presented here:

Heat production (Q_1) by the relaxation of the photogenerated carriers within the bands when $h\nu > E_g$ can be given¹² by:

$$Q_1 = \beta(\lambda) N_0(\lambda) \exp[-\beta(\lambda)(x+d)](h\nu - E_g) \quad \dots(1)$$

where $N_0(\lambda)$ is the surface photon flux; $\beta(\lambda)$, the optical absorption coefficient of the photo excited material at the excitation wavelength; d the junction depth; $h\nu$ the photon energy and E_g is the bandgap energy.

If photons with an energy $h\nu$ greater than E_g are incident on a semiconductor, the absorption of energy initiates the generation of electron-hole pairs. The relaxation of these photogenerated carriers within the bands produces heating.

Heat generation (Q_2) due to absorption processes not generating free carriers is written¹³ as:

$$Q_2 = N_0(\lambda)[1 - \beta(\lambda) \exp\{-\beta(\lambda)(x+d)\}]h\nu \dots (2)$$

Due to photon absorption, the transition of the carriers from upper quantum state to lower quantum state produces heat due to radiative recombination.

Joule heating for electrons and holes (Q_3) is given⁴ by:

$$Q_3 = \frac{1}{e} \left[J_n(x, t) \frac{dE_c}{dx} + J_p(x, t) \frac{dE_v}{dx} \right] \dots (3)$$

where e is the electronic charge; J_n , J_p the electron and hole current density and E_c , E_v are the conduction and valence-band energies, respectively. The expression Q_3 represents the junction heating and away from junction, it describes the usual Joule heating caused by an effective phonon emission, as electrons/holes drift along a slope in the band structure.

Heat production (Q_4) by Auger and SRH recombination is given¹⁴ by:

$$Q_4 = E_g (np - n_i^2) \left[\frac{1}{\tau_{po}(n + n_i) + \tau_{no}(p + n_i)} + \frac{r(n + p)}{n_i^2} \right] \dots (4)$$

where n and p are the electron and hole carrier concentration, respectively; n_i the intrinsic concentration and τ_{po} , τ_{no} , are the appropriate hole and electron lifetimes, which are taken as: $\tau_{po} = 3.5 \times 10^{-8}$ s, $\tau_{no} = 1.1 \times 10^{-8}$ s, r is the Auger recombination rate. Its value is chosen as $r = 2 \times 10^{-31}$ cm⁶/s, respectively.

In Auger recombination process, a fast electron or a fast hole loses KE in generating a electron-hole pair, e.g., two electrons and a hole or two holes and an electron take part in heating the crystal lattice. In SRH recombination, the crystal lattice is heated by release of energy during capture and emission by traps.

Heat generation (Q_5) due to relaxation, phonon recombination, radiative recombination and non-radiative recombination can be represented¹⁵ as:

$$Q_5 = J^2(t) \left[\frac{2^{7/2}}{\pi^{3/2}} \frac{\epsilon^2}{z^2 e^2 n_i} (kT)^{3/2} F(\epsilon) \left(\frac{n}{m_n^{*1/2}} + \frac{p}{m_p^{*1/2}} \right) \right]^{-1} +$$

$$+ kT \sum_{qp} \ln \left(2 \sinh \frac{h\nu_{qp}}{2KT} \right) + E_g N_o \eta_G \times$$

$$(E_c - E_v) \left[32\pi^2 c \left(\frac{kT}{ch} \right)^4 \times \int_{U_o}^{\infty} \frac{n'^3 kU^3}{\exp U - 1} dU \right]$$

$$\times [1 - \beta(\lambda) \exp\{-\beta(\lambda)(x + d)\}] \dots (5)$$

where J is the total current density; $\epsilon = 3KT$; $F(\epsilon)$, a function of energy; m_n^* , m_p^* , the effective electron and hole masses, n the refractive index; K the absorption index, c , the speed of light; respectively.

$$U = \frac{h\nu}{KT}; h\nu_{qp}, \text{ the photon energy for } qp \text{ mode.}$$

$$F(\epsilon) = \ln \left(1 + \frac{8m^* \epsilon}{q^2 \hbar^2} \right) - \left(1 + \frac{q^2 \hbar^2}{8m^* \epsilon} \right)^{-1}$$

where, $q = [4\pi e^2 N(\epsilon_F)]^{1/2}$ is the screening parameter; $\hbar = \frac{h}{2\pi}$ and $N(\epsilon_F)$ is the density of states at the Fermi surface.

The relaxation process is included due to direct interaction between hot carriers and thermal phonons. Energy flows from carriers to thermal phonons of the lattice, thereby heating the lattice. In phonon recombination process, interaction between hot carriers and phonon modes of the lattice excites the phonon mode. This excited phonon mode then interacts with thermal phonons through phonon-phonon interaction and causes heating of the lattice. The radiative recombination process is obtained through the effective distribution of photon density at thermal equilibrium and the absorption probability of photons per unit time.

Peltier heating (Q_6) for electrons and holes is given by⁸:

$$Q_6 = \nabla \cdot [(\Pi_n - \phi_n)J_n - (\Pi_p + \phi_p)J_p] \dots (6)$$

where, ϕ_n and ϕ_p are the quasi-Fermi potentials for electrons and holes, respectively. Peltier coefficient for electrons is defined by:

$$\Pi_n = \frac{1}{q} [E_c - \mu^{(n)} + \frac{3}{2} k T] + \Pi_n^0 \quad \dots(7)$$

where, $\mu^{(n)} = -q\phi_n$. Π_n^0 lies in the range between $\frac{1}{2} \frac{k T}{q}$ to $\frac{5}{2} \frac{k T}{q}$. Similarly, the Peltier coefficient for holes is defined by:

$$\Pi_p = \frac{1}{q} [E_v - \mu^{(p)} + \frac{3}{2} k T] + \Pi_p^0$$

where, $\mu^{(p)} = q\phi_p$; $\Pi_n J_n$ is a part of an electronic heat current and its divergence is a measure of the amount of power deposited to or taken up from an infinitesimal region of the crystal due to instantaneous change in particle current density. Some part of this term describes convection and heating due to band-gap narrowing.

Heating due to electron-hole scattering (Q_7) is given⁸ by:

$$Q_7 = \mathbf{E} \cdot (\nabla \phi_n + \nabla \phi_p) \sigma_{np}$$

where, $\mathbf{E}$ is the electric field and σ_{np} is a transport coefficient describing the effects of electron-hole scattering.

Under heavy doping condition, the expressions of n and p can be written as:

$$n = n_i F_{1/2}(\eta_n) \exp(-\eta_n) \exp \frac{E_{fn} - E_i}{KT} \exp \left(\frac{A \Delta E_g}{KT} \right)$$

$$p = n_i F_{1/2}(\eta_p) \exp(-\eta_p) \exp(1-A) \frac{\Delta E_g}{KT} \exp \left(\frac{E_i - E_{fp}}{KT} \right) \quad \dots(8)$$

where $F_{1/2}$ is the Fermi integral of order $1/2$; η_n , η_p , the reduced Fermi energy for electron and hole, respectively; ΔE_g , the bandgap narrowing; E_i the intrinsic Fermi energy; A the asymmetry factor, and E_{fn} , E_{fp} are the quasi-Fermi energy of electron and hole, respectively.

In thermal equilibrium, $E_{fn} = E_{fp}$. It is assumed that thermal equilibrium is attained under modulated photo-excitation. Also, it has been considered that the

thermal and/or carrier to thermal conversion gradients produced within the sample are not so sharp, due to which thermal equilibrium may be construed. Thus, taking the sum of Eqs(1) to (8), the expression for the effective heat generation in opto-electronic devices can be written as:

$$Q_{\text{eff}} = -\frac{1}{e} [J_n(x, t) \frac{dE_c}{dx} + J_p(x, t) \frac{dE_v}{dx}] +$$

$$+ E_g n_i^2 \left\{ \frac{F_{1/2}(\eta_n) F_{1/2}(\eta_p)}{\exp(\eta_n + \eta_p)} \exp \frac{\Delta E_g}{KT} - 1 \right\} \times$$

$$\times \left[\frac{1}{\tau_{po} n_i \left\{ F_{1/2}(\eta_n) \exp(-\eta_n) \exp \frac{\Delta E_g}{KT} \exp \left(\frac{E_{fn} - E_i}{KT} \right) + 1 \right\}} + \right.$$

$$+ \tau_{no} n_i \left\{ F_{1/2}(\eta_p) \exp(-\eta_p) \times \right.$$

$$\left. \exp(1-A) \frac{\Delta E_g}{KT} \exp \left(\frac{E_i - E_{fp}}{KT} \right) + 1 \right\}]$$

$$+ r n_i \left\{ \frac{A \Delta E_g}{KT} \exp \left(\frac{E_n - E_i}{KT} \right) \right.$$

$$\left. + F_{1/2}(\eta_n) \exp(1-A) \frac{\Delta E_g}{KT} \right.$$

$$\left. + \frac{F_{1/2}(\eta_p) \exp(1-A) \frac{\Delta E_g}{KT}}{\exp(\eta_p)} \times \right.$$

$$\left. \exp \left(\frac{E_i - E_{fp}}{KT} \right) \right\} + J^2(t) \left[\frac{2^{7/2}}{\pi^{3/2}} \frac{\epsilon^2}{z^2 e^2} (KT)^{3/2} F(\epsilon) \times \right.$$

$$\left. \frac{A \Delta E_g}{KT} \exp \left(\frac{E_{fn} - E_i}{KT} \right) \right.$$

$$\times \left\{ \frac{m_n^{*1/2} \exp(\eta_n)}{\dots} \right\}$$

$$\begin{aligned}
& + \frac{F_{1/2}(\eta_p) \exp(1-A) \frac{\Delta E_g}{KT} \exp\left(-\frac{E_i-E_{fp}}{KT}\right)}{m_p^{*1/2} \exp(\eta_p)} \}^{-1} + \\
& + kT \sum_{qp} \ln \left(2 \sinh \frac{\hbar v_{qp}}{2KT} \right) \times \\
& \times E_g \left[32\pi^2 c \left(\frac{kT}{ch} \right)^4 \int_{U_0}^{\infty} \frac{n^3 kU^3}{\exp U - 1} dU \right] + \\
& + \beta(\lambda) N_0(\lambda) \exp[-\beta(\lambda)(x+d)] (h\nu - E_g) + \\
& + N_0(\lambda) [1 - \beta(\lambda) \exp\{-\beta(\lambda)(x+d)\}] h\nu + \\
& + \mathbf{E} \cdot (\nabla \phi_n + \nabla \phi_p) \sigma_{np} + \\
& + E_g N_0 \eta_G [1 - \beta(\lambda) \exp\{-\beta(\lambda)(x+d)\}] + \\
& + \nabla \cdot [(\Pi_n - \phi_n) J_n - (\Pi_p + \phi_p) J_p] + \\
& + \mathbf{E} \cdot (\nabla \phi_n + \nabla \phi_p) \sigma_{np} \quad \dots(9)
\end{aligned}$$

3 Results

Crystal lattice is heated owing to recombination processes. In Auger recombination, two electrons and a hole or two holes and an electron produce lattice heating, whereas in Shockley-Read-Hall (SRH) recombination process, capture and emission of electrons by empty traps produce lattice heating. In relaxation process, lattice heating occurs as a result of energy flow from hot carrier to the thermal phonon of the lattice. Phonon-phonon interaction causes lattice heating in phonon recombination process. Most of the processes that generate heat within semiconductor devices have been taken into account in the expression of effective heat generation given by Eq. (9). Numerical computation of Eq. (9) is carried out for heavily doped silicon device. The bandgap narrowing is taken as¹⁶ $\Delta E_g(N) = 10.23 (N/10^{18})^{1/3} +$

$13.12 (N/10^{18})^{1/4} + 2.93 (N/10^{18})^{1/2}$ meV, $T = 300\text{K}$. The values of η_p , η_n , $F_{1/2}(\eta_p)$ and $F_{1/2}(\eta_n)$ are chosen suitably¹⁷ for the specified dopant densities and these are incorporated in the analysis.

The nature of variation of heat dissipation with carrier concentration is shown in Fig.1. The solid line curve (a) depicts the results of the present work, while the broken line curve (b) is obtained from numerical analysis of the theoretical results of an earlier work⁸. The curves show higher dissipation rates at higher concentrations. The plots of heat dissipation versus distance from the junction to the bulk are shown in Fig.2, where the results of the present analysis along with the earlier work are given. For two values of carrier concentration ($n=5 \times 10^{18}$ and $n=5 \times 10^{19}$), two sets of graphs have been drawn. The solid line curves (a) and (b) show the results of the present analysis, whereas the broken line curves (c) and (d) are due to the earlier work⁸. Heat dissipation rate remains almost constant throughout the region from the junction to the bulk in the present result, while in the previous result⁸, it falls off slowly within a short distance from the junction towards the bulk and then maintains almost a constant value.

4 Discussion

There are some disagreements, which are more towards the higher values of carrier concentrations.

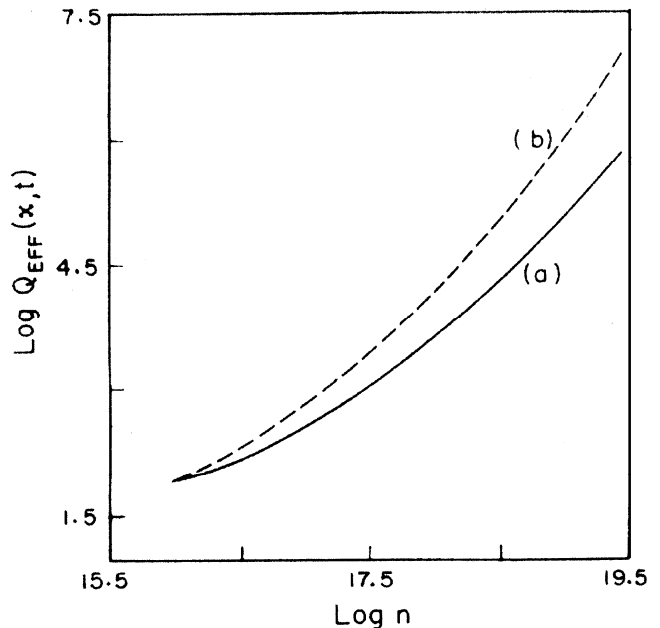


Fig. 1 — Plots of heat dissipation versus carrier concentration. The curve (a) shows the variation of the present result and the curve (b) is shown based on the numerical analysis of the theoretical results of an earlier work⁸.

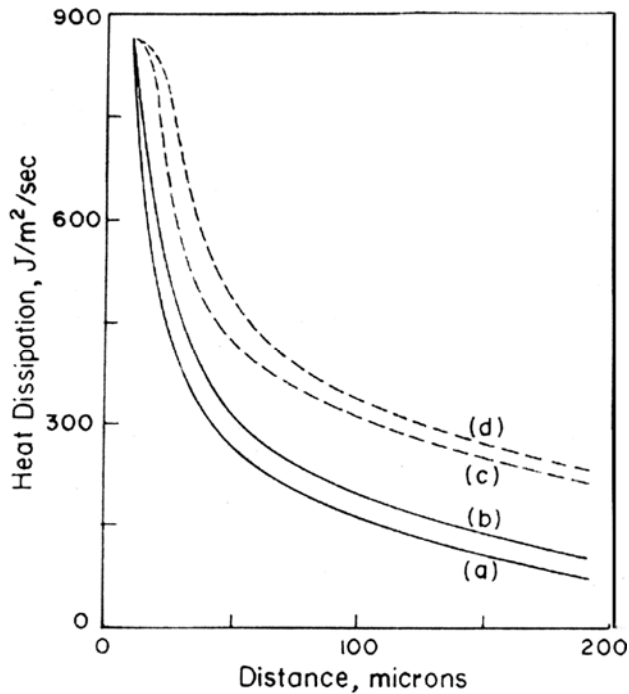


Fig. 2 — Plots show the heat dissipation versus distance from the junction to the bulk. The curves (a) and (b) represent the numerical results of the present work while the curves (c) and (d) are due to an earlier work⁸. Two sets of curves are for two concentrations. For (a) and (c), $n = 5 \times 10^{18}$, whereas for (b) and (d), $n = 5 \times 10^{19}$.

This is due to the difference between the two formulations during the application of high field. Numerical computation reveals that the contribution due to relaxation phenomenon is physically insignificant at higher carrier concentration in comparison to the effects due to phonon recombination and radiative recombination. But its effect is not ignorable for low carrier concentration. Most of the contributions of heating mechanism are operative up to 20 to 25°C above room temperature. It is very difficult to come up with a universal theory covering all device structures. As a result, the optical excitation inducing a barrier modulation in p - n junction devices^{12,18} that generates thermal contribution, has not been considered here. Also, the optical absorption depth profile is not taken into account in this analysis^{12,18}. Self-heating in devices introduces significant temperature increase during operation. For a power MOSFET, the temperature rise

is assumed to have an increased value of about 25°C above the room temperature¹⁹. Knowledge of internal self-heating effects in power transistor helps to study the transistor behaviour under high current and high voltage operating conditions³. It is found that at lower temperature, the channel mobility increases with increasing temperature. Device heating penetrates into the substrate causing band bending. This leads the threshold voltage to shift with heating. Because of want of experimental data, it is not possible to judge the superiority in between this method and the earlier theoretical work⁸.

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