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Electrothermal Analysis of Latch-Up in an Insulated Gate Transistor (IGT)

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SUMMARY An advanced model for self-heating effects in power semiconductor devices is derived from principles of irreversible thermodynamics. The importance of the entropy balance equation is emphasized. The governing equations for the coupled transport of charge carriers and heat are valid in both the stationary and transient regimes. Four characteristic effects contributing to the heat generation can be identified: Joule heating, recombination heating, Thomson heating and carrier source heating. Bandgap narrowing effects are included. Hot carrier effects are neglected. Numerical methods to solve the governing equations for the coupled transport of charge carriers and heat are described. Finally, results obtained in simulating latch-up in an IGT are discussed.

key words: *simulation, latch-up, IGT, thermodynamic, entropy*

1. Introduction

In order to allow accurate computation of device characteristics and analysis of parasitic effects in modern power semiconductor devices, the electrothermal nature of such phenomena as thermal runaway, current crowding, avalanche injection, secondary breakdown and latch-up has to be accounted for. Realizing electrothermal effects a transport model for the simultaneous flow of charge carriers and heat is needed.

From a numerical point of view the simulation of transient self-heating effects in semiconductor devices requires the self-consistent solution of Poisson's equation, the continuity equations for electrons and holes and the heat flow equation in space and time.

Following a rigorous approach to treat self-heating effects, the ansatz and the derivation of the governing equations for the coupled transport of charge carriers and heat are discussed in Sect. 2. In Sect. 3, the numerical methods used to solve the system of nonlinear, coupled partial differential equations describing electrothermal interaction are described. Results obtained in investigating latch-up in an IGT are presented in Sect. 4.

2. The Mathematical Model

To derive a closed set of equations for the simultaneous flow of charge carriers and heat in a semiconductor device, principles of irreversible thermodynamics are utilized [3], [7], [9]. The idea is to explicitly set up the entropy balance equation for the semiconductor, to identify thermodynamic currents and conjugated forces, and to formulate the phenomenological equations. To obtain governing equations describing mutually coupled electrothermal transport phenomena, transport parameters have to be defined and specific state functions have to be evaluated [3], [7], [9].

Provided that the concept of local equilibrium is valid, the Gibbs fundamental equation for the semiconductor takes the form:

$$\frac{\partial u}{\partial t}=T\cdot\frac{\partial s}{\partial t}-q\cdot\varphi_n\cdot\frac{\partial n}{\partial t}+q\cdot\varphi_p\cdot\frac{\partial p}{\partial t} \tag{1}$$

u denotes the total internal energy per unit volume, s the entropy density. n means the electron, p the hole concentration. T is the temperature, φ_n, φ_p are the quasi-Fermi levels for electrons and holes, respectively, with q being the elementary charge. Note that u includes the energy due to the applied and built-in potential too.

The Gibbs equation (1) interrelates balances of electrodynamic and thermodynamic quantities. Usually continuity equations for charge carriers together with Poisson's equation are derived from Maxwell's equations [10].

$$\operatorname{div}\vec{J}_n-q\cdot\frac{\partial n}{\partial t}=q\cdot R \tag{2}$$

$$\operatorname{div}\vec{J}_p+q\cdot\frac{\partial p}{\partial t}=-q\cdot R \tag{3}$$

$\vec{J}_n$, $\vec{J}_p$ represent the current densities for electrons and holes, respectively. The net recombination rate R is introduced by definition [10]. The conservation equation for the total internal energy u reads:

$$\frac{\partial u}{\partial t}+\operatorname{div}\vec{J}_u=0 \tag{4}$$

$\vec{J}_u$ is the energy flux vector. Equation (4) represents the first axiom of thermodynamics in terms of vector analysis for continuous systems. Momentum balance equations are not considered, thus neglecting hot car-

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rier effects. The actual form of the entropy balance equation is obtained by substitution of continuity equations for the carrier concentrations n, p and the energy density u into the Gibbs fundamental equation (1),

$$\frac{\partial s}{\partial t}+\mathrm{div}\left(\frac{1}{T}\cdot\vec{J}_h\right) = \vec{J}_h\cdot\left(-\frac{1}{T^2}\cdot\mathrm{grad}\ T\right)+\vec{J}_n\cdot\left(-\frac{1}{T}\cdot\mathrm{grad}\ \varphi_n\right) + \vec{J}_p\cdot\left(-\frac{1}{T}\cdot\mathrm{grad}\ \varphi_p\right)+R\cdot\left(\frac{1}{T}\cdot q\cdot(\varphi_p-\varphi_n)\right) \tag{5}$$

where

$$\vec{J}_h\equiv\vec{J}_u-\varphi_n\cdot\vec{J}_n-\varphi_p\cdot\vec{J}_p \tag{6}$$

is a definition of the heat flux $\vec{J}_h$.

The right-hand side of (5) is the local production of entropy. Due to the first postulate of irreversible thermodynamics it can be interpreted as the sum of products of thermodynamic currents and conjugated forces. Furthermore, exploiting the second postulate of irreversible thermodynamics, that each flux linearly depends on all thermodynamic forces [3], the so-called phenomenological equations result:

$$\begin{bmatrix}\vec{J}_n\\ \vec{J}_p\\ \vec{J}_h\\ R\end{bmatrix}=\begin{bmatrix}L_{nn} & 0 & L_{nT} & 0\\ 0 & L_{pp} & L_{pT} & 0\\ L_{Tn} & L_{Tp} & L_{TT} & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}-\frac{1}{T}\mathrm{grad}\ \varphi_n\\ -\frac{1}{T}\mathrm{grad}\ \varphi_p\\ -\frac{1}{T^2}\mathrm{grad}\ T\\ \frac{1}{T}\cdot q\cdot(\varphi_p-\varphi_n)\end{bmatrix} \tag{7}$$

Due to Onsager's symmetric reciprocal relations, known as the third postulate of irreversible thermodynamics, the number of independent kinetic coefficients in Eq.(7) can be reduced. Thus only conductivities σ and thermoelectric powers P for electrons n and holes p, respectively, have to be defined, together with the thermal conductivity $\varkappa$.

$$\sigma_n\equiv\frac{L_{nn}}{T}\quad P_n\equiv-\frac{L_{nT}}{T^2\cdot\sigma_n}$$

$$\sigma_p\equiv\frac{L_{pp}}{T}\quad P_p\equiv\frac{L_{pT}}{T^2\cdot\sigma_p}$$

$$\varkappa\equiv\frac{L'_{TT}}{T^2}-\sigma_n\cdot P_n^2\cdot T-\sigma_p\cdot P_p^2\cdot T \tag{8}$$

The resulting current relations (9)-(11) for the thermoelectric transport in a semiconductor include both limiting cases, (i) flow of electric charge due to the imposition of the quasi-Fermi potential, and (ii) flow of heat caused by a temperature gradient:

$$\vec{J}_n=\sigma_n\cdot(-\mathrm{grad}\ \varphi_n+P_n\cdot\mathrm{grad}\ T) \tag{9}$$

$$\vec{J}_p=\sigma_p\cdot(-\mathrm{grad}\ \varphi_p-P_p\cdot\mathrm{grad}\ T) \tag{10}$$

$$\vec{J}_h=-T\cdot P_n\cdot\vec{J}_n+T\cdot P_p\cdot\vec{J}_p-\varkappa\cdot\mathrm{grad}\ T \tag{11}$$

If Eqs.(9)-(11) are reformulated in terms of the total current density $\vec{J}=\vec{J}_n+\vec{J}_p$ and the heat flux $\vec{J}_h$, the thermal conductivity $\varkappa$ has to be redefined in order to include the bipolar contribution. L'_{TT} subsumes a lattice, an electron and a hole contribution.

With the heat flux (11) the entropy balance equation (5) can be transformed into the heat flow equation (12):

$$T\cdot\frac{\partial s}{\partial t}+\mathrm{div}(-T\cdot P_n\cdot\vec{J}_n+T\cdot P_p\cdot\vec{J}_p-\varkappa\cdot\mathrm{grad}\ T) =-\vec{J}_n\cdot\mathrm{grad}\ \varphi_n-\vec{J}_p\cdot\mathrm{grad}\ \varphi_p+q\cdot R\cdot(\varphi_p-\varphi_n) \tag{12}$$

The expansion of the divergence operator and some algebraic operations yield:

$$\begin{aligned}T\cdot\frac{\partial s}{\partial t}&+\mathrm{div}(-\varkappa\cdot\mathrm{grad}\ T)\\ &=\frac{\vec{J}_n\cdot\vec{J}_n}{\sigma_n}+\frac{\vec{J}_p\cdot\vec{J}_p}{\sigma_p}\\ &\quad+\vec{J}_n\cdot(\mathrm{grad}(T\cdot P_n)-P_n\cdot\mathrm{grad}\ T)\\ &\quad-\vec{J}_p\cdot(\mathrm{grad}(T\cdot P_p)-P_p\cdot\mathrm{grad}\ T)\\ &\quad+q\cdot R(\varphi_p-\varphi_n)\\ &\quad+T\cdot P_n\cdot\mathrm{div}\ \vec{J}_n-T\cdot P_p\cdot\mathrm{div}\ \vec{J}_p\end{aligned} \tag{13}$$

The right-hand side of Eq.(13) is the heat generation. It can be shown that (13) implies Thomson's laws.

The entropy density has to be regarded as a state function of the temperature and the carrier concentrations $s=s(T, n, p)$. Furthermore, the quasi-Fermi levels are considered as state functions of the electrostatic potential ψ, the carrier concentrations n, p, the temperature T, and the effective intrinsic carrier concentration n_{ie} to fit heavy doping effects [10]. Using Maxwell's relations [3], [12] and Boltzmann statistics the following system of nonlinear, coupled, partial differential equations results:

$$\mathrm{div}(\varepsilon\cdot\mathrm{grad}\ \psi)=-q\cdot(p-n+C) \tag{14}$$

$$\mathrm{div}\ q\cdot\mu_n\cdot n\cdot\left(\vec{E}-\frac{k\cdot T}{q}\cdot\mathrm{grad}(\ln n_{ie})+\frac{k\cdot T}{q}\cdot\frac{1}{n}\cdot\mathrm{grad}\ n+P_n^{eff}\cdot\mathrm{grad}\ T\right) =q\cdot\frac{\partial n}{\partial t}+q\cdot R \tag{15}$$

$$\mathrm{div}\ q\cdot\mu_p\cdot p\cdot\left(\vec{E}+\frac{k\cdot T}{q}\cdot\mathrm{grad}(\ln n_{ie})\right.$$

$$-\frac{k\cdot T}{q}\cdot\frac{1}{p}\cdot\operatorname{grad} p - P_p^{eff}\cdot\operatorname{grad} T\Big)$$
$$= -q\cdot\frac{\partial p}{\partial t} - q\cdot R \tag{16}$$

$$C_h\cdot\frac{\partial T}{\partial t}+\operatorname{div}(-\varkappa\cdot\operatorname{grad} T) = G_h^J + G_h^R + G_h^T + G_h^S \tag{17}$$

$$G_h^J = \frac{J_n^2}{\sigma_n}+\frac{J_p^2}{\sigma_p} \tag{18}$$

$$G_h^R = q\cdot R\Big(2\cdot T\cdot\frac{kT}{q}\cdot\frac{1}{n_{ie}}\cdot\frac{\partial n_{ie}}{\partial T}\Big) \tag{19}$$

$$G_h^T = \vec{J}_n\cdot T\cdot\operatorname{grad} P_n - \vec{J}_p\cdot T\cdot\operatorname{grad} P_p \tag{20}$$

$$G_h^S = T\cdot P_n^{eff}\cdot\operatorname{div}\vec{J}_n - T\cdot P_p^{eff}\cdot\operatorname{div}\vec{J}_p \tag{21}$$

$$\Big(\frac{k}{q}\cdot\ln\frac{c}{n_{ie}}-\frac{kT}{q}\cdot\frac{1}{n_{ie}}\cdot\frac{\partial n_{ie}}{\partial T}\Big)+P_c\equiv P_c^{eff} \tag{22}$$

Equation (14) is the well known Poisson equation. ψ denotes the electrostatic potential, C the total net concentration of all ionized impurities. ε is the permittivity. Equations (15), (16) are continuity equations for electrons n and holes p including the so-called extended-drift extended-diffusion approximation of the current relations. That is, an effective electric field is introduced because of the possible dependence of the intrinsic concentration on position, and the diffusion not only accounts for concentration gradients but also for temperature gradients. μ denotes the mobility, k the Boltzmann constant. $\vec{E}$ is the electric field, P the thermoelectric power, c means 'carrier' and may take the value n or p for electrons and holes, respectively. Equation (17) is the heat flow equation. C_h denotes the heat capacity. The right-hand side in (17) represents the heat generation. Four contributions to the heat generation can be distinguished: Joule heat G_h^J (18), recombination heat G_h^R (19), Thomson heat G_h^T (20) and carrier source heat G_h^S (21). Equation (22) is a definition of the effective thermoelectric power P_c^{eff}. The expression in brackets arises due to the dependence of the quasi-Fermi potential on temperature.

The governing equations depend non-linearly on the lattice temperature. If lattice heating is significant, the thermal system becomes tightly coupled to the electrical system. Recombination, mobility, thermoelectric power and the effective intrinsic carrier density n_{ie} depend on temperature [10], while the temperature gradient acts as a driving force and the heat generation is a function of the electrical variables.

Auger recombination and carrier-carrier scattering, known as limiting physical effects for high injection conditions in power semiconductor devices [10], have been taken into account. As heavy doping effects limit thyristor operation, the effective intrinsic carrier concentration is computed using [10], [11]. One obtains the relation:

$$\frac{\partial n_{ie}}{\partial T} = n_{ie}\cdot\Big(\frac{E_g}{2\cdot k\cdot T^2}+\frac{3}{2\cdot T}\Big)$$
$$-n_{ie}\cdot\left(\frac{q\cdot V_1\cdot\left(\ln\left(\frac{N_D^+ + N_A^-}{N_0}\right)+\sqrt{\ln^2\left(\frac{N_D^+ + N_A^-}{N_0}\right)+0.5}\right)}{2\cdot k\cdot T^2}\right)$$
$$+n_{ie}\cdot\left(\frac{9.025\cdot 10^{-5}\frac{eV}{K}+6.10\cdot 10^{-7}\frac{eV}{K}\cdot\left(\frac{T}{K}\right)}{2\cdot k\cdot T}\right)$$
$$+n_{ie}\cdot\left(\frac{3}{4}\cdot m_0\cdot\left(\frac{1.4\cdot 10^{-4}\frac{1}{K}\cdot m_n^* + 4.5\cdot 10^{-4}\frac{1}{K}\cdot m_p^*}{m_n^*\cdot m_p^*}\right)\right) \tag{23}$$

Note also that the dependence of the bandgap energy E_g and the effective masses on temperature is accounted for in Eq. (23). Following [4], [8] the thermoelectric powers can be expressed as functions of contributions to the overal mobility [6].

For the electrical subsystem, either Dirichlet boundaries at ohmic contacts or Neumann boundaries are assumed. Mixed boundary conditions for the heat flow equation are mandatory in order to be able to model realistic imperfect cooling conditions. This is of special importance for transient electrothermal simulations, as the time constant for self-heating increases with increasing external thermal resistance.

3. Solution Methods

The simulation of the coupled transport of heat and charge carriers requires the self-consistent solution of Poisson's equation (14), the continuity equations for electrons n (15) and holes p (16) and the heat flow equation (17) in space and time. Spatial discretization is obtained using finite boxes [5], a generalization of finite differences, while time is discretized with the backward Euler method.

The electrothermal problem is computed self-consistently following a decoupled approach. At each time step the electrical subsystem of equations is solved first, the lattice temperature being regarded as an independent variable. Then the temperature distribution is updated by solving the heat flow equation. Newton's method and LU-decomposition are used to solve the electrical and thermal subsystems alternately until convergence is attained.

Usually, the characteristic time for the electrical and the thermal subsystem differ by several orders of magnitude. Thus a device is in steady state from the electrical point of view, whereas thermally it is still in transition.

4. Results

An IGT combines bipolar conduction with MOS gate control of the current. Due to bipolar conductivity modulation arising from carrier injection into the n^--drift region an IGT can be operated at high forward current densities, even when supporting high blocking voltages. Due to its MOS gate the IGT can be driven with low power.

The concept of the IGT is to use a MOS gate created channel to link the n^+-emitter region to the n^--base [2]. In the on-state the lower junction towards the collector is forward-biased and the current flow in the IGT occurs via the channel. When latch-up occurs, however, the parasitic thyristor between the collector and emitter terminals in the four-layer IGT structure turns on, and the control of the collector current by the applied gate voltage is lost. In DC circuits latch-up usually produces catastrophic failure of the device as a result of excessive heat dissipation.

Static latch-up has been investigated in an IGT. It occurs when the forward conduction current density exceeds a critical value, while the collector voltage is low. Geometry and doping data of the IGT have been taken from [2]. The simulation area contains only one half of a symmetric IGT cell. Figure 1 shows a cross section of the most interesting part of the IGT with respect to latch-up analysis. The n^+-emitter ($1\cdot 10^{20}\,\mathrm{cm}^{-3}$) is embedded in a double doped p-base region ($1\cdot 10^{18}\,\mathrm{cm}^{-3}$, $5\cdot 10^{16}\,\mathrm{cm}^{-3}$). In order to support a blocking voltage of 300 V the n-drift layer ($1\cdot 10^{15}\,\mathrm{cm}^{-3}$) has been chosen to be 65 μm long. The bottom of the simulation area is made up of a 10 μm p^+-doped substrate ($1\cdot 10^{19}\,\mathrm{cm}^{-3}$) which cannot be seen in Fig. 1. A n-buffer layer is not included.

Figures 2 and 3 show the electron and hole concentration in the critical part of the IGT, containing the emitter and p-base region, under equilibrium conditions. Figures 1, 2 show how both, the p-base region together with the n^+-emitter are incorporated in the lightly doped n-type drift layer, which is the central region of the IGT.

In order to find the critical value of the collector current I_c, the collector voltage V_{ce} has been ramped in a transient electrothermal simulation first. Then the electrothermal steady-state solution has been computed for $V_{ge}=15$ V, $V_{ce}=1.5$ V. The idea is to investigate one bias point (from the electrical point of view) but to modify the conditions for self-heating. Thus the current handling capability of the IGT limited by the onset of latch-up can be investigated as a function of lattice temperature determined by different thermal conditions.

Two different thermal boundary conditions have been chosen. First very good cooling conditions (heat sink thermal conductance $h=50\,\mathrm{W/cm^2K}$), then realistic cooling conditions ($h=5\,\mathrm{W/cm^2K}$) have been assumed. In the latter case a second simulation has been performed based on a heuristic heat generation model [1], [10]:

$$G_h=(J_n+J_p)\cdot\vec{E}+R\cdot E_g \tag{24}$$

Equation (24) accounts for two contributions to the overal heat generation, Joule heat with the electric field as a driving force and recombination heat considering the contribution of the bandgap only. Double sided cooling is assumed. The heat sink temperature T_o is

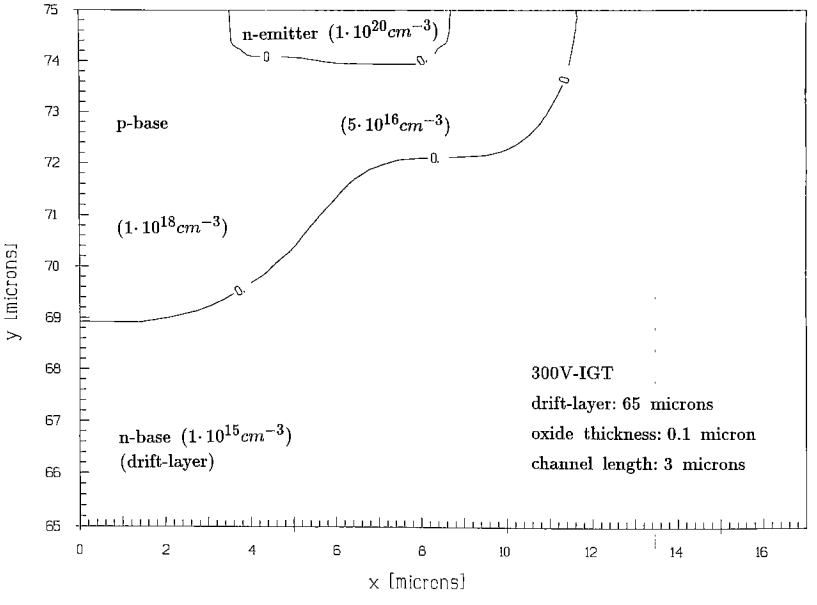

Fig. 1 cross section of IGT, (n^+-emitter ($1\cdot 10^{20}\,\mathrm{cm}^{-3}$), onset of n-base ($1\cdot 10^{15}\,\mathrm{cm}^{-3}$) p-base ($1\cdot 10^{18}\,\mathrm{cm}^{-3}$, $5\cdot 10^{16}\,\mathrm{cm}^{-3}$)).

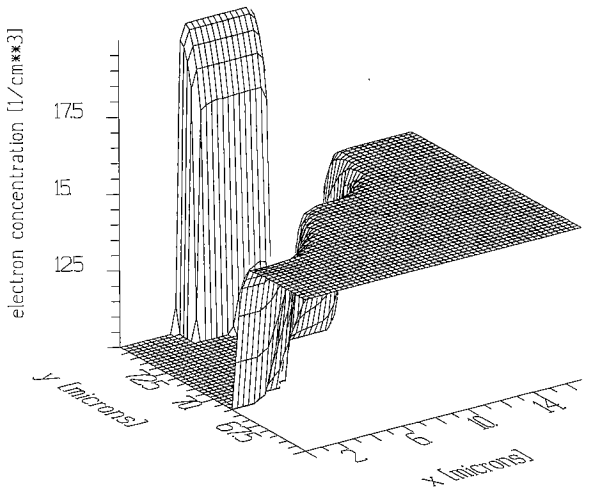

Fig. 2 electron concentration [cm^{-3}] for equilibrium, $V_{ge}=0$ V, $V_{ce}=0$ V.

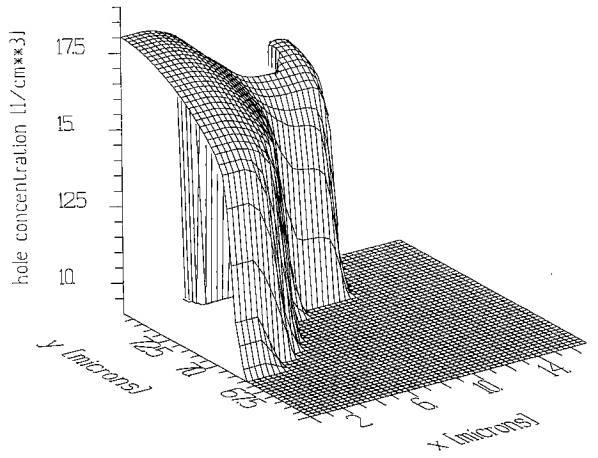

Fig. 3 hole concentration [cm^{-3}] for equilibrium, $V_{ge}=0$ V, $V_{ce}=0$ V.

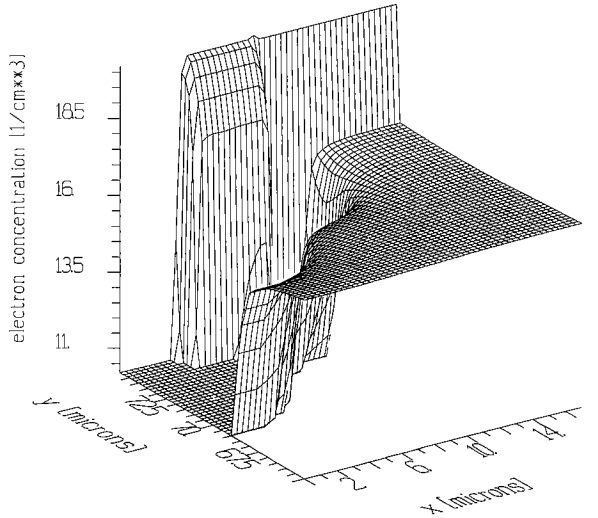

Fig. 4 electron concentration [cm^{-3}], SOA, $V_{ge}=15$ V, $V_{ce}=1.5$ V, $T_o=300$ K, $h=50$ W/cm^2K.

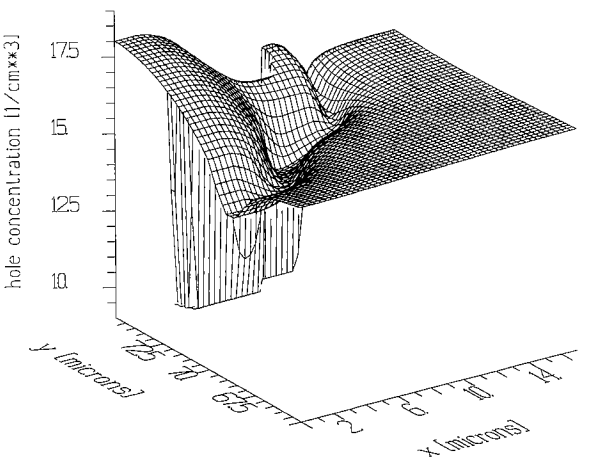

Fig. 5 hole concentration [cm^{-3}], SOA, $V_{ge}=15$ V, $V_{ce}=1.5$ V. $T_o=300$ K, $h=50$ W/cm^2K.

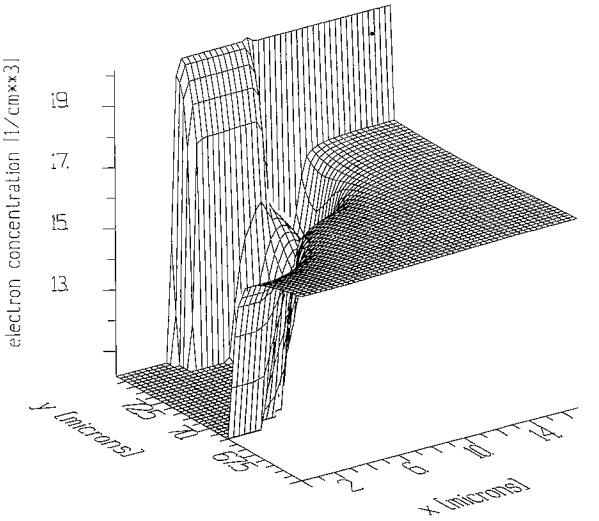

Fig. 6 electron concentration [cm^{-3}], Latch-Up, $V_{ge}=15$ V, $V_{ce}=1.5$ V, $T_o=300$ K, $h=5$ W/cm^2K.

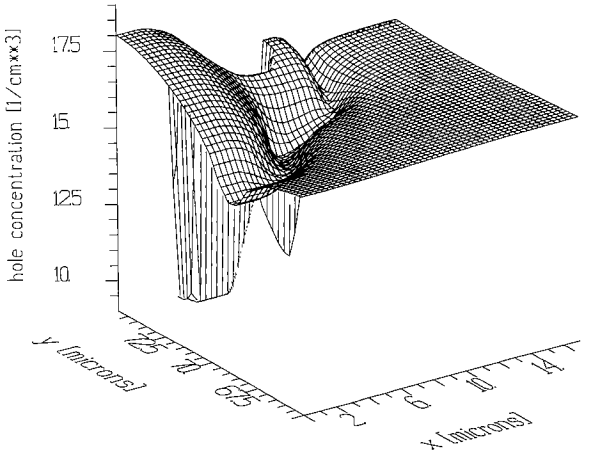

Fig. 7 hole concentration [cm^{-3}], Latch-Up, $V_{ge}=15$ V, $V_{ce}=1.5$ V, $T_o=300$ K, $h=5$ W/cm^2K.

300 K in all simulations.

When the heat sink thermal conductance is 50 W/cm^{2}K the IGT is still in the save operating area (SOA). The peak lattice temperature is 305.2 K in this case. Figures 4, 5 show the carrier concentration in the n^+-emitter, the channel region and the p-base. Latch-up, however, is very pronounced for a heat sink thermal conductance 5 W/cm^{2}K. The corresponding peak lattice temperature is 346.1 K. Figures 6, 7 present the electron and hole concentration for the onset of latch-up. Note that the difference between Figs. 4, 5 and 6, 7 is due to different cooling conditions only. In both cases $V_g=15$ V, $V_c=1.5$ V have been applied. Thus it is demonstrated that latch-up in the IGT has to be regarded as an electrothermal problem.

The increase of lattice temperature, however, is not only determined by thermal boundary conditions but also by the local heat production. Using the heuristic heat generation model (24), (incorporated in many device simulators), the peak lattice temperature is predicted to be 329.5 K ($h=5$ W/cm^{2}K unchanged). Latch-up is much less pronounced. This fact indicates

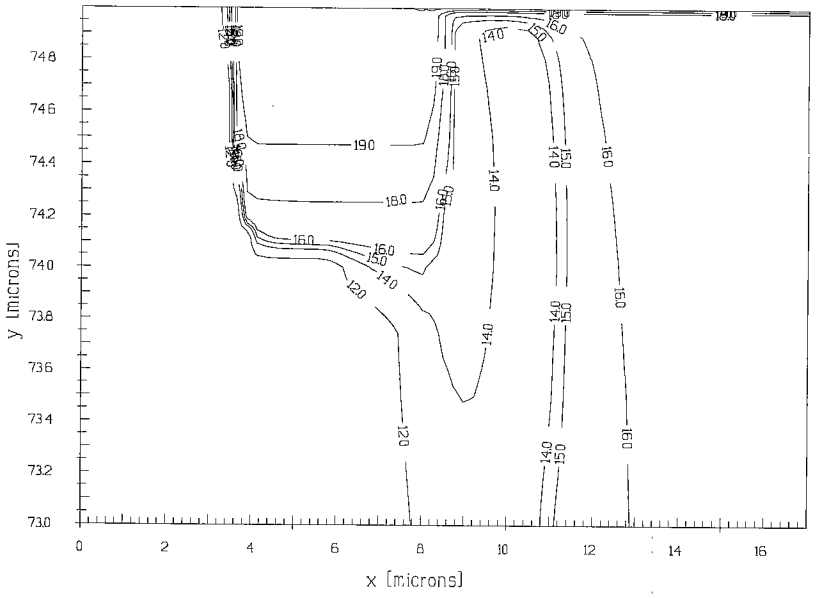

Fig. 8 contour lines of electron concentration [cm^{-3}] for Latch-Up, $V_{ge}=15$ V, $V_{ce}=1.5$ V, $T_o=300$ K, $h=5$ W/cm^{2}K.

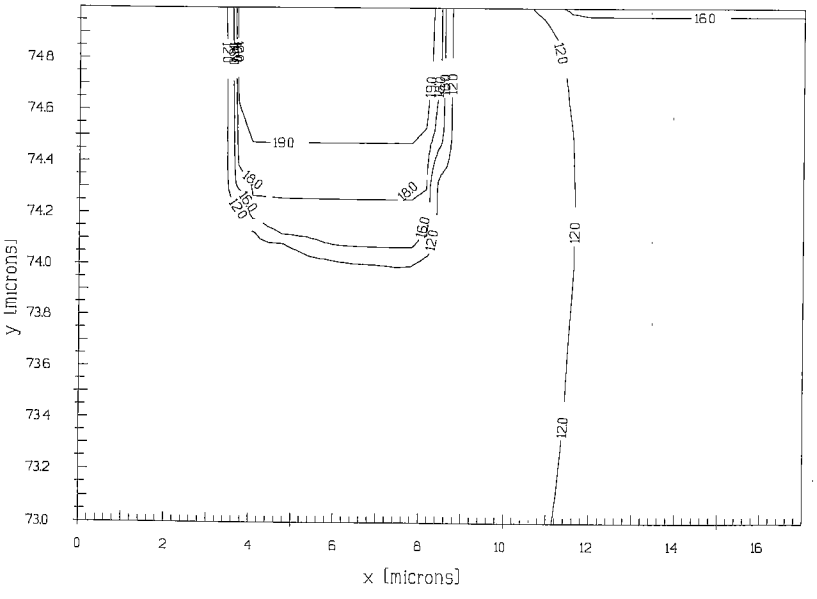

Fig. 9 contour lines of electron concentration [cm^{-3}] for equilibrium, $V_{ge}=0$ V, $V_{ce}=0$ V.

that the capability to accurately predict the safe operating area depends on the availability of an advanced model for local energy conversion.

When latch-up occurs the emitter injects electrons into the p-base as is made visible in Fig. 6. The emitter region spreads into the p-base, as is seen from Fig. 8 by comparison with the equilibrium distribution in Fig. 9, initiating the turn on of the parasitic thyristor in the IGT-structure.

In order to compare the different levels of injected electrons the IGT has been cut at the emitter edge for Fig. 10. The electron concentration in the p-base rises with the increase of lattice temperature.

In isothermal silicon at 300 K, the critical value for the onset of latch-up is exceeded when the n^+-emitter-p-base junction becomes forward-biased by more than 0.7 volt, usually because of lateral current flow in the p-base. Under non-isothermal conditions, however, the junction voltage is reduced which can be seen in Fig. 11. Therefore more electrons are injected. Furthermore the voltage drop in the p-base due to hole current flow is higher in the non-isothermal case because of the increase of the sheet resistance due to the excess lattice temperature. This effect is made visible in Fig. 12.

Figure 13 shows the excess temperature in the channel region after onset of latch-up. The maximum

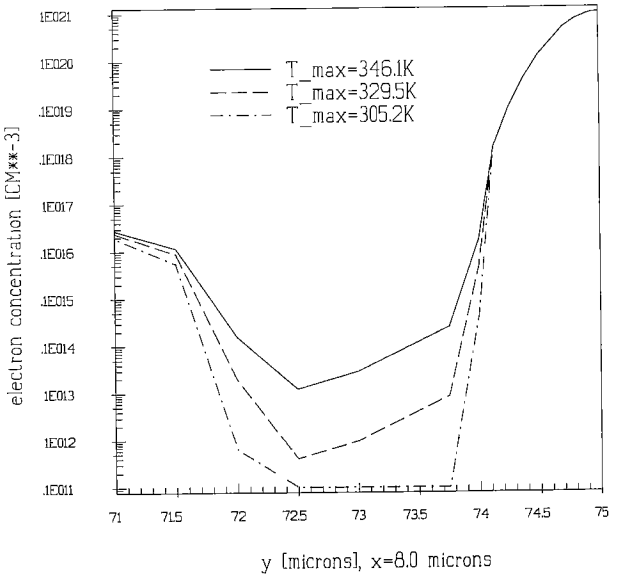

Fig. 10 comparison of electron concentration [cm^{-3}] at $x=8.0$ μm, $V_{ge}=15$ V, $V_{ce}=1.5$ V. $h=50$ W/cm^{2}K, $h=5$ W/cm^{2}K.

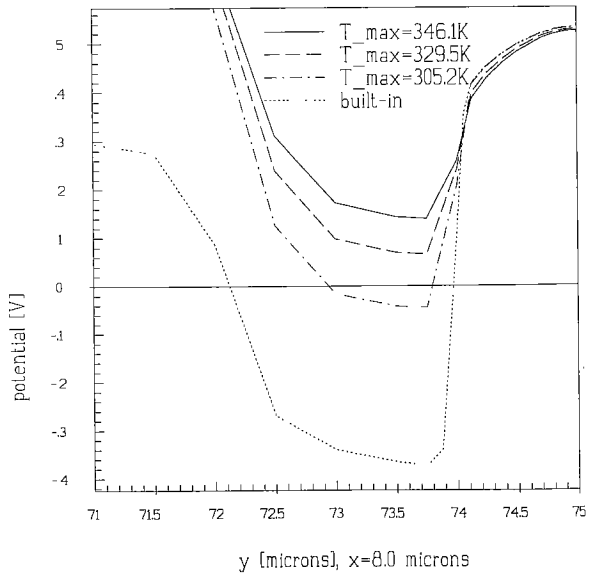

Fig. 11 comparison of potential [cm^{-3}] at $x=8.0$ μm, $V_{ge}=15$ V, $V_{ce}=1.5$ V. $h=50$ W/cm^{2}K, $h=5$ W/cm^{2}K.

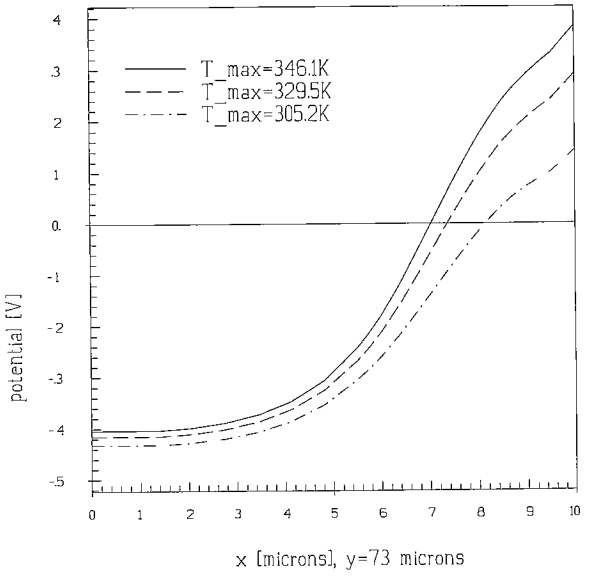

Fig. 12 comparison of potential [cm^{-3}] at $y=73$ μm, $V_{ge}=15$ V, $V_{ce}=1.5$ V. $h=50$ W/cm^{2}K, $h=5$ W/cm^{2}K.

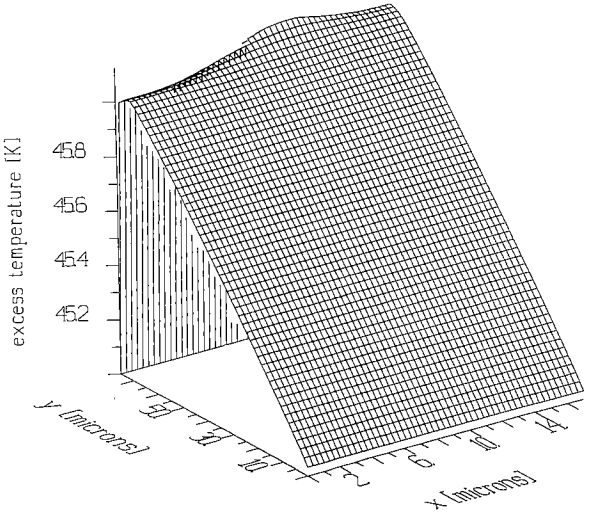

Fig. 13 excess temperature [K], Latch-Up, $V_{ge}=15$ V, $V_{ce}=1.5$ V, $T_o=300$ K, $h=5$ W/cm^{2}K.

temperature is found to be 346.1 K for the conditions cited above. The temperature distribution is almost homogeneous. Most of the temperature drop is external to the device. The temperature peak is located in the inversion layer due to excessive Joule heating.

It is found that the latching current is reduced with increasing temperature. The reason is that the gain of the *pnp*-transistor as well as the sheet resistance of the *p*-base increases with temperature. Furthermore the reduction of the n^+-emitter-*p*-base junction voltage due to self-heating enhances latch-up. Thus the latching current reduction is a function of cooling conditions.

5. Conclusion

Emphasizing the entropy balance equation an advanced model for self-heating effects has been derived from principles of irreversible thermodynamics. It is valid in both the stationary and the transient regimes.

Four contributions to the heat generation can be distinguished: Joule heat, recombination heat, Thomson heat and carrier source heat.

The electrothermal nature of device behavior during latch-up in an IGT has been simulated. It has been found that accurate analysis of latch-up phenomena requires electrothermal simulation to account for the reduction of latching current due to self-heating. Furthermore it has been shown that simulations based on a heuristic model of electrothermal transport tend to predict a larger save operating area of the IGT than simulations based on the suggested rigorous model of electrothermal interaction.

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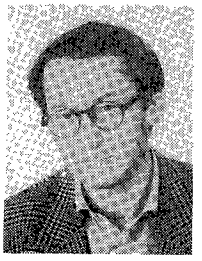

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