# Improved Modeling Of Bandgap-Narrowing Effects in Silicon $p^+/n^+$ Junctions

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Abstract

A generalized model for bandgap narrowing effects is developed. It takes into account the individual dependency of conduction- and valence band edge on doping level. Our model includes the common formulation as a special case of symmetric decrease of the effective densities of states in the conduction and valence bands with rising doping level, and yields a new formulation of emitter efficiency in bipolar devices. The new model is verified by direct measurements of emitter efficiency in Shorted-Anode Lateral IGBTs

## 1.Introduction

The correct description of bandgap-narrowing effects is necessary for the simulation of most bipolar devices since bandgap-narrowing severely reduces the emitter efficiency of highly-doped emitters. In bipolar high-frequency devices, high base doping levels are used to reduce base resistance, and current gain is limited by emitter efficiency. In bipolar power devices (IGBTs, thyristors, diodes) $p^+$-emitter/$n^+$-buffer combinations are frequently used to reduce the drift-zone thickness, and the properties of the emitter/buffer junction chiefly determine the high-injection plasma density in the lowly doped drift region. The emitter efficiency of $p^+/n^+$-junctions is of great importance for the simulation of these two types of devices.

In today's simulation tools, bandgap-narrowing-effects are included using a phenomenological model for the doping dependence of the intrinsic carrier density $n_i$ [1,2]. Using the definition for electron and hole quasi-fermi potentials (for Boltzmann statistics)

$$n = n_i \exp\left(\frac{q}{kT}\left(\psi - \phi_n\right)\right) \; ; \; p = n_i \exp\left(\frac{q}{kT}\left(-\psi + \phi_p\right)\right) \qquad (1),$$

one obtains with $j_n = -\sigma_n \nabla\phi_n \; ; j_p = -\sigma_p \nabla\phi_p$ the current equations

$$j_n = \sigma_n\left(\mathrm{E} - \tfrac{kT}{q}\nabla \ln n_i\right) + qD_n\nabla n \; ; j_p = \sigma_p\left(\mathrm{E} + \tfrac{kT}{q}\nabla \ln n_i\right) - qD_p\nabla p \qquad (2).$$

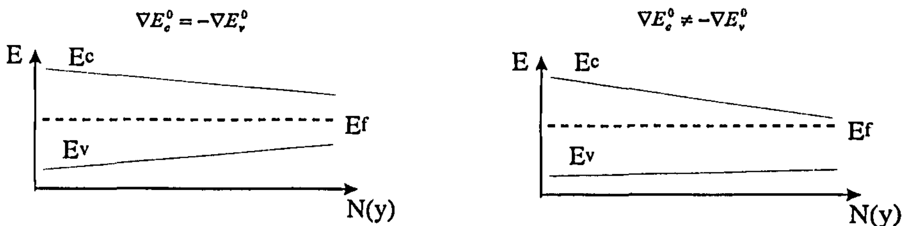
Performing the analysis of current transport in according to equation (2), one obtains the well known formula for the emitter efficiency of a p-emitter [2]

$$\gamma_p = \left(1 + \int_{d_A}^{d_n} \frac{N_D^{Buffer}(y)dy}{n_i(y)D_p(y)} \Bigg/ \int_0^{d_A} \frac{N_A^{Emitter}(y)dy}{n_i(y)D_p(y)}\right)^{-1} \qquad (3)$$

In eq. (2), the effect of bandgap-narrowing on electron and hole current density is modeled by the introduction of an additional field $-\frac{kT}{q}\nabla \ln n_i$ for electrons, and $\frac{kT}{q}\nabla \ln n_i$ for the holes.

## 2. Modeling

However, if one analyses the electron and hole current densities in terms of microscopic driving forces, bandgap-narrowing effects are incorporated in gradients of conduction and valence band edges, respectively. As far as we know, there is neither a theoretical argument nor experimental evidence for the assumption that conduction and valence band edges should behave in the same way under the influence of high doping. (Fig. 1)




a) b)

**Fig. 1:** Schematic of bandgap narrowing with rising doping level for a) assuming symmetric effect on conduction and valence band edge b) more general asymmetric distribution of bandgap-lowering

Assuming that carrier drift motion is initiated either by electrostatic field or by the spatial gradient of the corresponding band edge (conduction or valence band for electrons and holes, respectively), one obtains in the framework of the drift-diffusion approximation the current equations

$$j_n = \sigma_n\left(\mathrm{E}+\tfrac{1}{q}\nabla E_c^0\right)+qD_n\nabla n \;;\; j_p = \sigma_p\left(\mathrm{E}+\tfrac{1}{q}\nabla E_v^0\right)-qD_p\nabla p \tag{4}$$

using the common definition of the imref gradients as generalized thermodynamical forces

$$j_n = -\sigma_n\nabla\phi_n \;;\; j_p = -\sigma_p\nabla\phi_p$$

we derive the relationships

$$n = N_C \exp\left(-\frac{E_c^0(y)-E_0}{kT}\right)\exp\left(\frac{q}{kT}(\psi-\phi_n)\right) = n_{i,n}(y)\exp\left(\frac{q}{kT}(\psi-\phi_n)\right) \tag{5a}$$

$$p = N_V \exp\left(\frac{E_v^0(y)-E_0}{kT}\right)\exp\left(\frac{q}{kT}(-\psi+\phi_p)\right) = n_{i,p}(y)\exp\left(\frac{q}{kT}(-\psi+\phi_p)\right) \tag{5b}$$,

where $E_c^0(y); E_v^0(y)$ are the doping dependent band edges and

$$E_0 = (E_c + E_v)/2 + (kT/2)\ln(N_v/N_c)$$

is the midgap energy of the lowly doped semiconductor.

Eq. (5a,b) includes the formulation (1) as a special case of the equality $\nabla E_c^0 = -\nabla E_v^0$ i.e. the case of symmetric decrease of the effective densities of states in the conduction and valence bands with rising doping level. According to (4,5), the expression for p-emitter efficieny (3) must be rewritten as

$$\gamma_p = \left(1 + \int_{d_A}^{d_n} \frac{N_D^{buffer}(y)dy}{n_{i,p}(y)D_p(y)} \Bigg/ \int_0^{d_A} \frac{N_A^{emitter}(y)dy}{n_{i,n}(y)D_p(y)}\right)^{-1} \tag{6}$$

## 3. Measurements

To verify our model, we performed measurements of the emitter efficiency in Shorted-Anode Lateral SOI-IGBTs [4]. (Fig. 2) with different buffer concentrations. The presence of separately contacted anode shorts enables a precise extraction of low-injection emitter efficiency of the p-anode by measurements of leakage currents. In two subsequent experiments we measure the leakage currents of the built-in diode by biasing the anode short only, and then determine the leakage current of the pnp-transistor by biasing the p-anode. The generation current from the space charge-region is the same for both operation conditions, but in the case of the biased p-anode, it is additionally amplified by hole injection. For moderate bias voltages of 100-200V, avalanche multiplication can be neglected and the p-emitter efficiency $\gamma_p$ can be extracted as

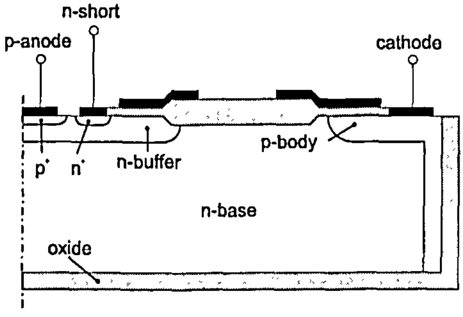



Fig. 2: Structure of the Lateral SOI-IGBT

$$\gamma_p = \left(I_{pnp} - I_{diode}\right)/I_{pnp} \,.$$

Fig. 3 shows the measured emitter efficiency for different doses of n-buffer implantation, as well as calculated values. Using the model introduced by del Alamo [3]

$$n_i(N) = n_i \exp\left(\Delta E_{bgn}/2kT\right);$$
$$\Delta E_{bgn}(N) = E_{bgn} \ln\left(N/N_{ref}\right)$$

we tried to fit the two parameters $E_{bgn}$ and $N_{ref}$ to give a good agreement with experimental results. As one can easily see, the fitted parameters match for low values of buffer doping. As buffer implantation dose increases to a level for which bandgap-narrowing in the n⁺-buffer begins to occur, the calculated emitter efficiencies become too low. It is not possible to achieve a good agreement for both high and low buffer dose with one set of parameters. Using our generalized model (4-6) and following the model of del Alamo

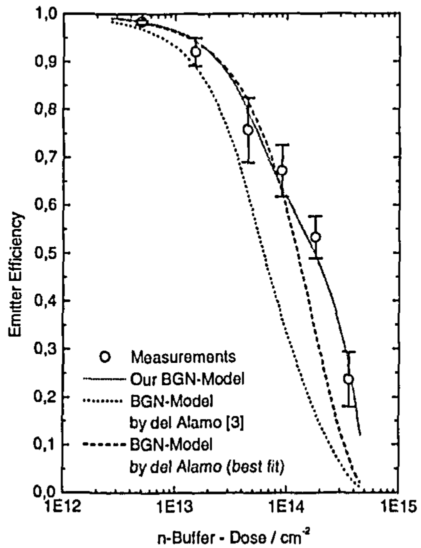



Fig. 3: Measured and calculated emitter efficiencies

$$n_{i,n}(N) = n_i \exp\left(\Delta E^n_{bgn}/2kT\right); \Delta E^n_{bgn}(N) = E^n_{bgn} \ln\left(N/N^n_{ref}\right)$$
$$n_{i,p}(N) = n_i \exp\left(\Delta E^p_{bgn}/2kT\right); \Delta E^p_{bgn}(N) = E^p_{bgn} \ln\left(N/N^p_{ref}\right)$$

we can achieve very good agreement with experimental data by using a different set of parameters for electrons and holes.

## 4. Summary

We propose a new generalized model of the effect of bandgap-narrowing on charge carrier transport which is based on microscopic considerations and includes the individual dependency of conduction- and valence band edge on doping level. Our model includes the conventional description (1-3) as a special case and yields good agreement with measured emitter efficiency of $p^+n$-junctions for both low and high n-doping. We believe that our generalized approach has the potential to resolve the contradictions between the different bandgap-narrowing models and parameter sets.

## References:

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