# DIRECT AND TRAP-ASSISTED TUNNELLING IN THE SCHOTTKY BARRIER

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## 1. Theory

The paper examines the effect of direct tunnelling (DT) and trap-assisted tunnelling (TAT) upon the gate leakage current in HEMT transistors on GaN. The gate contact consists of a Schottky barrier. *I-V* characteristics of the Schottky junction are extremely sensitive to defect-assisted tunnelling. In our model, four processes of electron and hole generation and recombination described by the SRH model are completed by four electron and hole capture and release processes of tunnelling to and from the traps, giving together eight exchange processes characterized by their escape times $\tau_R^e$, $\tau_G^e$, $\tau_R^h$, $\tau_G^h$, $\tau_{TCB}^e \equiv \tau_{CBT}^e$ and $\tau_{MT}^e \equiv \tau_{TM}^e$. From these eight exchange processes one can derive the TAT generation-recombination rates occurring in the continuity equations for electrons and holes.

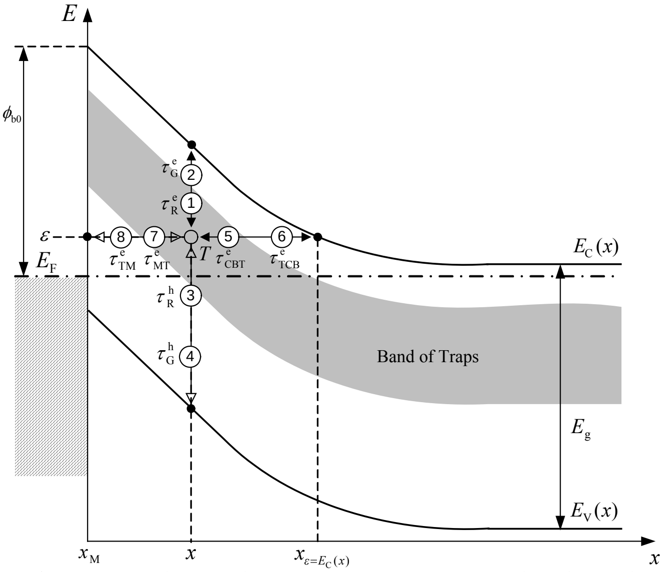


Fig. 1: *Eight exchange processes involved in the new model of trap-assisted band-to-band tunnelling.*

The well known continuity equation for electrons can be written as

$$\frac{dJ_D^e}{q\,dx} = U_{SRH_{TAT}} + U_{TAT}^{e(THER)} + U_{TAT}^{e(TUN)} + U_{DT}^e\,, \tag{1}$$

where the modified SRH recombination rate is

$$U_{SRH_{TAT}}(x) = \int\limits_{E_V(x)}^{E_C(x)} \frac{\dfrac{1}{\tau_R^e}\dfrac{1}{\tau_R^h} - \dfrac{1}{\tau_G^e}\dfrac{1}{\tau_G^h}}{\dfrac{1}{\tau_R^e} + \dfrac{1}{\tau_G^e} + \dfrac{1}{\tau_G^h} + \dfrac{1}{\tau_R^h} + \dfrac{1}{\tau_{CBT}^e} + \dfrac{1}{\tau_{MT}^e}} D_t\,d\varepsilon, \tag{2}$$

$U_{DT}^e$ is the electron recombination rate of direct tunnelling, and the two components of the electron recombination rate of trap-assisted tunnelling are given as integrals

$$U_{\mathrm{TAT}}^{\mathrm{e(THER)}}(x)=\int_{E_{\mathrm{V}}(x_s)}^{E_{\mathrm{C}}(x)}\frac{\frac{1}{\tau_{\mathrm{R}}^{\mathrm{e}}}\left(\frac{1-f_{\mathrm{M}}}{\tau_{\mathrm{MT}}^{\mathrm{e}}}+\frac{1-f_{\mathrm{F_n}}(x_\varepsilon)}{\tau_{\mathrm{CBT}}^{\mathrm{e}}}\right)-\frac{1}{\tau_{\mathrm{G}}^{\mathrm{e}}}\left(\frac{f_{\mathrm{M}}}{\tau_{\mathrm{MT}}^{\mathrm{e}}}+\frac{f_{\mathrm{F_n}}(x_\varepsilon)}{\tau_{\mathrm{CBT}}^{\mathrm{e}}}\right)}{\frac{1}{\tau_{\mathrm{R}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{G}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{G}}^{\mathrm{h}}}+\frac{1}{\tau_{\mathrm{R}}^{\mathrm{h}}}+\frac{1}{\tau_{\mathrm{CBT}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{MT}}^{\mathrm{e}}}}D_{\mathrm{t}}\,\mathrm{d}\varepsilon, \tag{3}$$

$$U_{\mathrm{TAT}}^{\mathrm{e(TUN)}}(x_\varepsilon)=|F_{\mathrm{C}}|\int_{x_{\mathrm{M}}}^{x_\varepsilon}\frac{\frac{f_{\mathrm{F_n}}(x_\varepsilon)}{\tau_{\mathrm{CBT}}^{\mathrm{e}}}\left(\frac{1}{\tau_{\mathrm{G}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{R}}^{\mathrm{h}}}+\frac{1}{\tau_{\mathrm{MT}}^{\mathrm{e}}}\right)-\frac{1-f_{\mathrm{F_n}}(x_\varepsilon)}{\tau_{\mathrm{CBT}}^{\mathrm{e}}}\left(\frac{1}{\tau_{\mathrm{R}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{G}}^{\mathrm{h}}}+\frac{f_{\mathrm{M}}}{1-f_{\mathrm{F_n}}(x_\varepsilon)}\frac{1}{\tau_{\mathrm{MT}}^{\mathrm{e}}}\right)}{\frac{1}{\tau_{\mathrm{R}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{G}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{G}}^{\mathrm{h}}}+\frac{1}{\tau_{\mathrm{R}}^{\mathrm{h}}}+\frac{1}{\tau_{\mathrm{CBT}}^{\mathrm{e}}}+\frac{1}{\tau_{\mathrm{MT}}^{\mathrm{e}}}}D_{\mathrm{t}}\,\mathrm{d}x. \tag{4}$$

Here, $x_\varepsilon$ is the position of the intersection of energy level ε with $E_{\mathrm{c}}(x)$, $f_{\mathrm{F_n}}(x_\varepsilon)$ and $f_{\mathrm{M}}$ are the Fermi-Dirac distribution functions for electrons in the semiconductor and metal, respectively, and $F_{\mathrm{C}}=\mathrm{d}E_{\mathrm{C}}(x)/\mathrm{d}x\big|_{x_\varepsilon}$ is the electron driving force. The formulae for calculating the thermal escape times are

$$\left(\tau_{\mathrm{R}}^{\mathrm{e}}(x)\right)^{-1}=v_{\mathrm{th}}^{\mathrm{e}}\sigma_{\mathrm{t}}\,n(x), \tag{5}$$

$$\left(\tau_{\mathrm{R}}^{\mathrm{h}}(x)\right)^{-1}=v_{\mathrm{th}}^{\mathrm{h}}\sigma_{\mathrm{t}}\,p(x), \tag{6}$$

$$\left(\tau_{\mathrm{G}}^{\mathrm{e}}(x)\right)^{-1}=v_{\mathrm{th}}^{\mathrm{e}}\sigma_{\mathrm{t}}N_{\mathrm{C}}\exp\left(\left(\varepsilon-E_{\mathrm{C}}(x)\right)/kT\right), \tag{7}$$

$$\left(\tau_{\mathrm{G}}^{\mathrm{h}}(x)\right)^{-1}=v_{\mathrm{th}}^{\mathrm{h}}\sigma_{\mathrm{t}}N_{\mathrm{V}}\exp\left(\left(E_{\mathrm{V}}(x)-\varepsilon\right)/kT\right) \tag{8}$$

and those for calculating the tunnelling escape times

$$\left(\tau_{\mathrm{CBT,MT}}^{\mathrm{e}}(x,\varepsilon)\right)^{-1}=\frac{m_{\mathrm{R}}^{\mathrm{e}}\sigma_{\mathrm{t}}}{2\pi^2\hbar^3}\int_{E_{\mathrm{C}}(x_{\mathrm{L}})}^{\varepsilon}|\varepsilon-\varepsilon'|\,\Gamma_{\mathrm{CBT,MT}}^{\mathrm{e}}(\varepsilon')\mathrm{d}\varepsilon', \tag{9}$$

where $m_{\mathrm{R}}^{\mathrm{e}}$ is the effective mass for calculating the Richardson constant in the semiconductor, $\Gamma_{\mathrm{CBT}}^{\mathrm{e}}$ and $\Gamma_{\mathrm{MT}}^{\mathrm{e}}$ are the probabilities of electron tunnelling, and $v_{\mathrm{th}}^{\mathrm{e,h}}=\sqrt{3kT/m_{\mathrm{e,h}}^{*}}$ are thermal velocities of charge carriers. Equations (2 to 9) were derived in a similar way like in our previous papers [1, 2] in which the method of escape times was used to model the charge transport through a MIM structure.

Definition of the distribution function of the traps in the band, $D_{\mathrm{t}}$, based on the theory of multiphonon assisted tunnelling can be found in [3].

Simulations of direct tunnelling were conducted with a displaced Maxwellian distribution function because outside thermodynamic equilibrium the electrons in the space charge region are under the influence of the electric field that imparts them a drift velocity limited by its saturation value. In such a case the generation-recombination rates can be expressed as

$$U_{\mathrm{DIR}}^{\mathrm{e(TUN)}}(x_\varepsilon)\cong\frac{qm_{\mathrm{R}}^{\mathrm{e}}}{2\pi^2\hbar^3}|F_{\mathrm{C}}|\Gamma_{\mathrm{DT}}^{\mathrm{e}}(\varepsilon)\exp\left(-\frac{E_{\mathrm{C}}(x_\varepsilon)}{kT}\right)\left\{\exp\left(\frac{E_{\mathrm{F_n}}(x_\varepsilon)}{kT}\right)F_{\mathrm{DIS}}^{\mathrm{e}}(x_\varepsilon)-\exp\left(\frac{E_{\mathrm{F_M}}}{kT}\right)\right\}, \tag{10}$$

where displacement function $F_{\mathrm{DIS}}^{\mathrm{e}}$ is defined as

$$F_{\mathrm{DIS}}^{\mathrm{e}}(x_\varepsilon)=\exp\left(-\xi^2(x_\varepsilon)\right)-\sqrt{\pi}\,\xi(x_\varepsilon)\mathrm{erfc}\left(\xi(x_\varepsilon)\right) \tag{11}$$

and $\xi$ is a dimensionless parameter

$$\xi(x_\varepsilon)=v_{\mathrm{DIS}}^{\mathrm{e}}(x_\varepsilon)/\sqrt{2kT/m_{\mathrm{T}}^{\mathrm{e}}}. \tag{12}$$

Here, $v_{\mathrm{DIS}}^{\mathrm{e}}$ is the velocity of displacement calculated as

$$v_{\mathrm{DIS}}^{\mathrm{e}}(x_\varepsilon) = \mu^{e}(x_\varepsilon)\left|\frac{\mathrm{d}\psi^{\mathrm{e}}(x_\varepsilon)}{\mathrm{d}x_\varepsilon} - \frac{kT}{q\,n(x_\varepsilon)}\frac{\mathrm{d}n(x_\varepsilon)}{\mathrm{d}x_\varepsilon}\right|. \tag{13}$$

The magnitude of the velocity of displacement is limited by the saturation velocity of electrons in GaN, $v_{\mathrm{sat}}^{\mathrm{e}} \cong 1.34\times10^{5}$ m/s [4].

## 2. Simulations

The new TAT model was employed to simulate a Schottky diode prepared on a silicon doped GaN substrate with donor concentration $N_{\mathrm{D}}$=2×10$^{18}$ cm$^{-3}$ and Schottky barrier height $\phi_{\mathrm{b0}}$=1.45 eV. In GaN, the Huang-Rhys factor is $S$=6.5 and the effective phonon energy $\hbar\omega_0$=0.066 eV [4, 5]. The concentration of traps was assumed to be $N_{\mathrm{t}}$=2×10$^{17}$ cm$^{-3}$ with effective trap cross-section $\sigma_{\mathrm{t}}$ =1×10$^{-18}$ m$^{-3}$. Effective masses $m_{\mathrm{R}}^{\mathrm{e}} = 0.2\ m_0$ were used to evaluate the tunnelling escape times $\tau_{\mathrm{CBT}}^{\mathrm{e}}$ and $\tau_{\mathrm{MT}}^{\mathrm{e}}$. The tunnelling probability was calculated using the WKB approximation and the effective masses were also set as $m_{\mathrm{T}}^{\mathrm{e}} = 0.2\ m_0$. The ohmic contact at the back size of the structure was loaded by serial resistivity $R_{\mathrm{ohm}}$=5×10$^{-6}$ Ωm$^{-2}$.

In the simulations of TED and DT in a forward biased structure, an important role belongs to the displacement function $F_{\mathrm{DIS}}^{\mathrm{e}}$. Its shape is shown in Fig. 2 along with the dependence of the dimensionless parameter ξ that follows the dependence of the displacement velocity $v_{\mathrm{DIS}}^{\mathrm{e}}$ on the applied voltage.

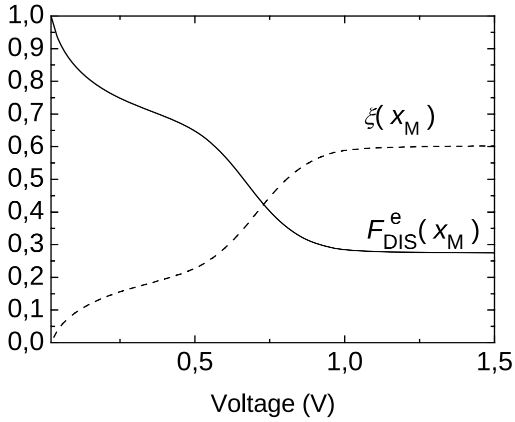


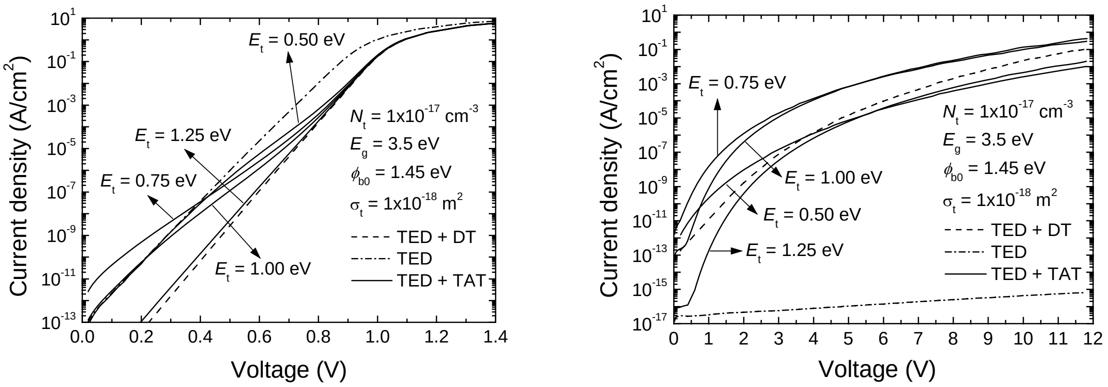
Fig. 2: *Displacement function $F_{\mathrm{DIS}}^{\mathrm{e}}$ and parameter ξ at the maximum of the Schottky barrier, $x_{\mathrm{M}}$, in dependence on the applied voltage in a forward biased Schottky structure.*

The *I-V* curves of such a Schottky structure were simulated at room temperature, $T$=300 K. In the simulations we considered three various models of charge transport through the Schottky barrier:

a) thermionic emission-diffusion model (TED),
b) TED model along with direct tunnelling (DT) between the metal and the conduction band of the semiconductor,
c) TED model along with trap-assisted tunnelling (TAT).

In all simulations we considered also the Schottky barrier lowering caused by the image force. To demonstrate the influence of TAT upon the charge transport we considered four different the distribution function $D_{\mathrm{t}}$ forms the band of traps at energy levels $E_{\mathrm{t}}$=0.5, 0.75, 1.0 and 1.25 eV from the conduction band edge (Figs. 3 and 4).

The simulated *I-V* curves prove that the TAT mechanism of charge transport dominates in a reverse biased Schottky structure, whereas in a forward biased structure the dominant mechanism of charge transport is direct tunnelling, DT. The $F_{\mathrm{DIS}}^{\mathrm{e}}$ function causes that at a voltage of 1 V the TED current drops down by more than 70%. At this voltage the displacement velocity $v_{\mathrm{DIS}}^{\mathrm{e}}$ settles at its saturation value whereby parameter $\xi$ saturates at $\xi = 0.6$.



Figs. 3 and 4: *Simulated forward and reverse I-V curves of Schottky diodes on GaN using different models of charge transport through the Schottky barrier.*

Simulations of *I-V* curves of real Schottky diodes require simultaneous consideration of all the three mechanisms of charge transport, thus TED + DT + TAT.

## 3. Conclusions

The presented TAT model of charge transport aims at explaining the origin of large leakage currents in reverse biased Schottky diodes shutting the 2D channel in high electron mobility transistors (HEMTs). It is obvious that multiphonon broadening of the band of traps together with trap-assisted tunnelling markedly affects the *I-V* curves of the diodes. The new TAT model has the ability to describe the generation and recombination as well as the tunnelling processes in Schottky junctions.

## Acknowledgement

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