A Compact Model for Polar Multiple-Channel Field Effect Transistors: A Case Study in III-V Nitride Semiconductors

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Multiple-channel field-effect transistors based on III-V Nitride semiconductors (GaN, AlN, InN, etc.) have been the subject of thorough investigation, promising low ON-resistance and high ON-current by overcoming the trade-off between carrier density and mobility [1, 2]. The performance of said devices is fundamentally governed by the distribution and control of mobile carriers. The distribution of electrons or holes directly impacts current transport and device reliability, and therefore the ability to predict and manipulate carrier populations is a critical point of control for device design and optimization. Despite this importance, there are limited analytical works pertaining to said systems. Instead, device modeling conventionally depends on computationally expensive numerical calculations, which inherently provide limited understanding of the underlying physics.

In this work we develop a compact analytical model for the mobile charge density of multiple channel field effect transistors (Fig. 1) based on the III-Nitride material system to provide a tractable, efficient and physically insightful framework to complement and guide numerical simulations. Focusing on the active region of devices that employ a multiple quantum-well layout, the total mobile electron and hole populations are estimated by the integration of fundamental electrostatic and quantum mechanical principles (Figs. 2 & 3). Hole gas depletion techniques, revolving around intentional donor doping, are modeled and evaluated, culminating in a generalized closed-form equation for the mobile carrier density across the doping schemes examined.

Consistent with both numerical calculations and experimental observations, the compact framework provided herein considerably elucidates and enhances the efficiency of multi-layered transistor design.

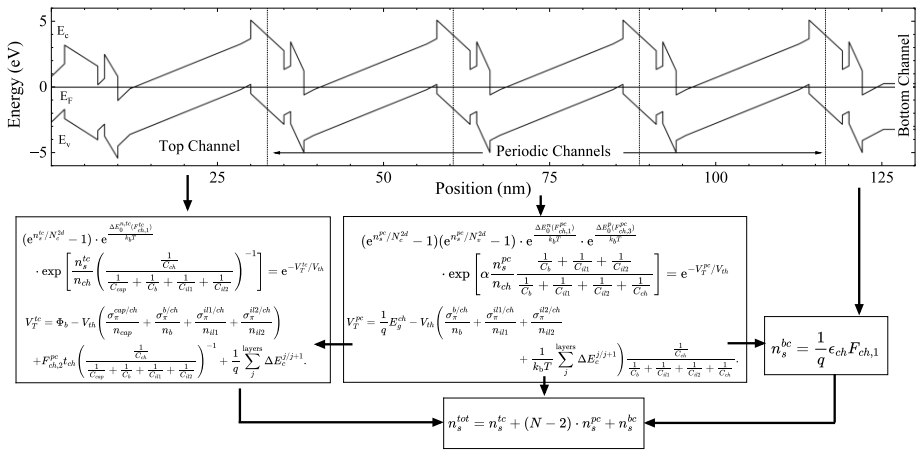

Figure 1: (Top) Energy band diagram of an indicative multi-channel field effect transistor. The active region is divided into three regions of interest: the top channel, periodic channels, and the bottom channel. (Bottom) Equation flow chart for 2DEG (n_s) calculation. $N_{c,v}^{2d} = g_s g_v m_{c,v}^* k_b T/2\pi\hbar^2$ is the 2D effective density of states at the conduction and valence band edge, respectively, with g_s, g_v being the spin and valley degeneracy, $m_{c,v}^*$ the effective mass of each band, k_b is the Boltzmann constant and T is temperature. $\Delta E_0^{n,p}$ is the first subband energy of the respective well. The parameter $\alpha \equiv (t_{ch} - z_n - z_p)/t_{ch}$, where t_{ch} is the channel layer thickness, and z_n, z_p are the positions of each 2D gas. The terms $C_x = \epsilon_x/t_x$ correspond to the capacitance of layer x (= cap, barrier, channel, interlayer), where ϵ_x is the permittivity and t_x the thickness of said layer. V_{th} is the thermal voltage $k_b T/q$, and $n_{ch} = C_{ch} V_{th}/q$. Φ_b is the surface barrier height, and F_x is the electric field strength at layer x. V_T is the critical condition for 2DEG/2DHG formation at each interface.

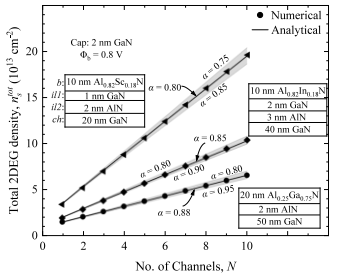

Figure 2: Total 2DEG density versus the number of channels for GaN-based heterostructures, calculated using the equations in Fig. 1. The numerical calculations were done with nextnano [3].

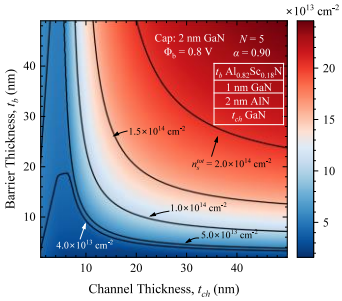

Figure 3: Contour plots of total 2DEG density as a function of channel and barrier thickness for 5-channel AlScN/1nm GaN/ 2nm AlN/GaN.

References

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