Introducing the Spiked *p-n* Junction for Tunnel Devices and Current Gain

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Introduction

By serendipity, a novel feature has appeared in regrown GaN *p-n* junctions. When the device is exposed to atmosphere in between the growth of the *n* and *p* regions, a sheet layer of donors (primarily oxygen) incorporates at the junction interface [1, 2]. This has been argued to decrease the depletion width, which boosts tunneling currents to acceptable levels for contacts to GaN LEDs [1].

While this is useful in its own right, a general analysis of the electrostatics of a sheet charge in a *p-n* junction yields another interesting regime not yet reported. Given sufficiently large interface charge, the *n*-side may enter accumulation, forcing a "spike" into an otherwise typical homojunction *p-n* band diagram. Such spikes may prove relevant for the design of tunnel junctions, or for homojunction gain elements (similar to the delta-doped BJTs of [3]).

Solution

Consider a *p-n* homojunction with uniform doping densities N_A and N_D, as well as an interface sheet charge density of $q\sigma$. For application to the chemical donor sheet discussed above, σ would be the concentration of *ionized* oxygen atoms, and depends on the local chemical potential. But we will treat a simpler model in which $q\sigma$ is constant; for this, one may imagine a polarization discontinuity charge between compound semiconductors of similar band structure [4].

In the simplest picture, the charge neutrality condition [5] familiar from *p-n* junctions, $qN_A x_p = qN_D x_n$, is modified to include sheet charge: $qN_A x_p = qN_D x_n + q\sigma$. Following standard depletion approximation arguments, one finds that, for $\sigma^2 \geq 2\varepsilon N_A \phi_b / q$, the *n*-side depletion region vanishes, so the device crosses into a new regime. Specifically, the *n*-side enters accumulation, and the band diagram spikes down at the interface, as shown in Figure 1(c). To illustrate the scales involved, note that a heavily doped GaN junction or GaAs junction with $N_A = 8{\times}10^{19}\text{cm}^{-3}$ would cross regimes at a sheet charge of around $\sigma_0 \sim 5.3 \times 10^{13}\text{cm}^{-2}$ or $\sigma_0 \sim 4.1 \times 10^{13}\text{cm}^{-2}$ respectively.

This work analytically solves the junction electrostatics in the "strong accumulation" regime (where the size of this spike, $q\Delta V_n$, is well beyond kT). A compact expression is derived for ΔV_n as a function of bias, a more precise expression is found for the regime cross-over, and suitable approximations are given for the band diagram near the spike. These formulae will enable engineers to design a variety of spiked *p-n* devices such as those suggested below.

Device Applications

Most notably, embedded sheet charge pulls the conduction and valence bands closer together (in real space) by consuming much of the depletion width, as depicted in Figures 2(b,c). When analyzed via the interband WKB formalism in [5, 7, 8], this should exponentially increase the reverse-bias tunneling currents. This particular feature provides benefit regardless of whether the device is in strong accumulation or not (for instance, the device in [1] is not).

Additionally, Figure 2(d) shows that, if the device *is* in strong accumulation, then, in forward bias, it presents a different barrier to transport of electrons versus holes, without the use of a bandgap-mismatched heterojunction. (A bandgap-mismatched heterojunction may be used in practice to produce the interface charge, but the effect studied here is, in principle, provided purely by electrostatics even in a homojunction.) Steeply discriminating between electron and hole currents is the essence of gain in bipolar junction transistors and a major motivation for modern heterojunction bipolar transistors [6]. So it is suggestive to see this barrier differentiation appear naturally in a homojunction system, and the device could be interpreted as a consolidated form of the delta-doped BJT [3]. Both of these effects are shown in the schematic *I-V* relation of Figure 2(a).

Achieving the strong accumulation regime represents an application specially suited for polarization engineering [4], rather than chemically-induced doping. First, chemically-introduced interface dopants would be almost entirely un-ionized if the device is in strong accumulation, thus providing very little net charge and contradicting the strong accumulation assumptions. Second, since the device behavior depends strongly on both the value of $q\sigma$ and its repeatable spatial sharpness, the exact and interfacial nature of polarization discontinuity charges is ideal. Future exploration of these polarization-enabled devices will be simplified by use of the analytic formulae derived here.

[1] Young et al., Applied Physics Express 9, 022102 (2016).
[2] Hu, Zongyang et al, *in preparation*.
[3] H. Wei et al. IET Circ. Dev. & Syst. 142, 406–412 (1995).
[4] Jena et al, Physica Status Solidi A 28, 1511-1516 (2011).
[5] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed.
[6] Rockett, *The Materials Science of Semiconductors*.
[7] A. C. Seabaugh and Q. Zhang, Proc. IEEE 98, 2095 (2010).
[8] D. Jena, Proc. IEEE 101, 1585 (2013).

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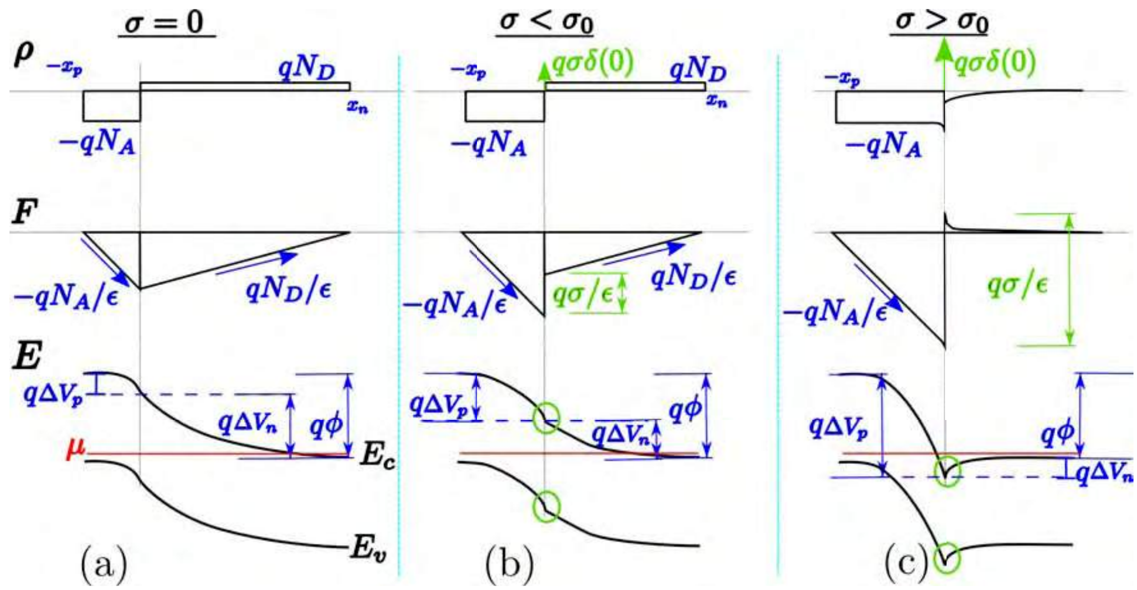

Fig. 1: Illustrative charge-field-band diagrams for the same *p-n* junction with various levels of sheet charge. **(a)** With $\sigma = 0$, the depletion approximation [5] yields a familiar triangular field profile. **(b)** For small σ, the triangular profile acquires a small discontinuity and rebalances appropriately. **(c)** For large σ, the field discontinuity forces a sign change in the field, and the depletion picture breaks down. The *n*-side enters accumulation and a spike appears in the band diagram. From depletion arguments, one can derive a approximate cross-over at $\sigma_0^2 \approx 2\varepsilon N_A \phi_b / q$.

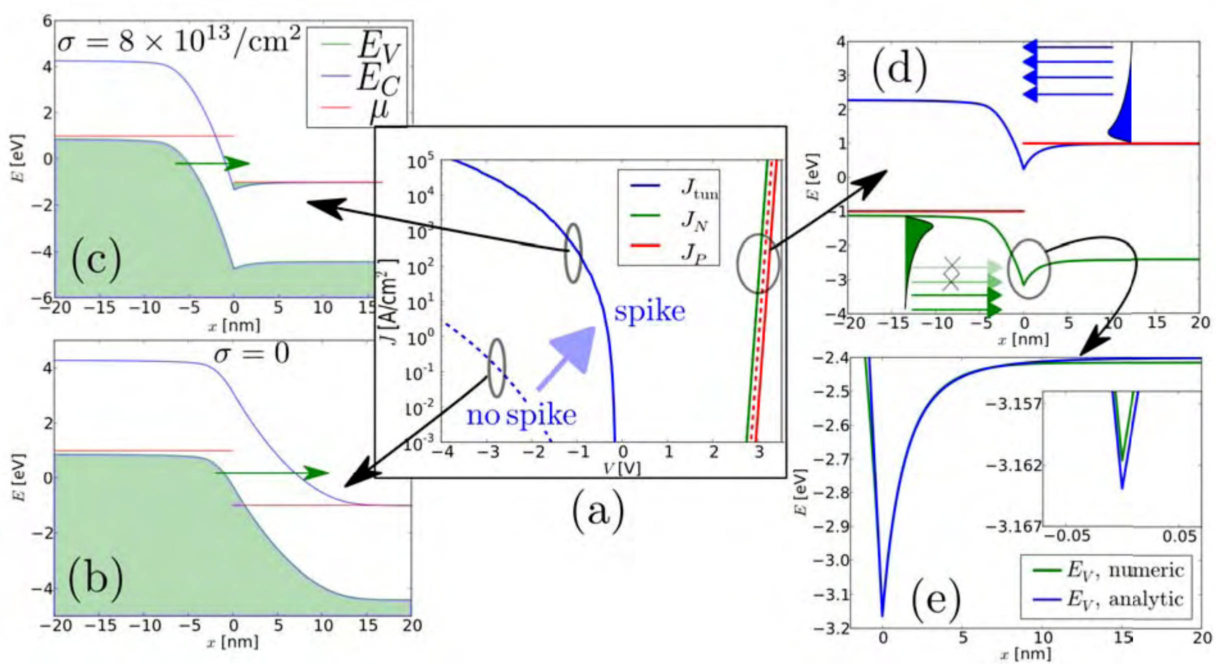

Fig. 2: **(a)** Estimated intrinsic currents for a hypothetical spiked junction (solid lines) and normal junction (dashed lines), showing the tunneling current (J_{tun}) in reverse bias, and the diode currents in forward bias with hole (J_P) and electron (J_N) components separated. **Reverse bias:** As shown in **(c)**, sheet charge bends the band diagram to to shorten the tunnel length, as compared to a normal junction in **(b)**. Consequently, the tunnel current in **(a)** is much higher for a spiked junction. **Forward bias:** The spike acts as a tunnel barrier to holes **(d)** but not to electrons. This suppresses the forward hole current as seen in **(a)**. In **(e)**, a zoom of the spike reveals an excellent match between the numerical band diagram (from a Poisson-solver) and analytic approximations derived here.