Some Semiconductor Device Physics Considerations and Clarifications

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***Abstract*—We present some clarifications of band diagrams, quasi-Fermi levels, and the channel shape of metal–oxide–semiconductor field-effect transistors that are frequently misrepresented in textbooks. We consider both simple first-order calculations and detailed computer simulations to show how these parameters are better represented.**

***Index Terms*—Metal–oxide–semiconductor field-effect transistors, quasi-Fermi levels, semiconductor device modeling.**

I. INTRODUCTION

IN THIS brief, we wish to comment on two aspects of semiconductor device physics that are frequently displayed incorrectly in textbooks and papers. These are quasi-Fermi levels in semiconductor devices and the channel shape of MOSFETs. Through first-order calculations/concepts, we show how these devices should be displayed. Then, through detailed computer simulations, we confirm our concepts. Our ultimate hope is that authors of textbooks and papers will consider these concepts.

II. QUASI-FERMI LEVELS

We begin by considering the quasi-Fermi levels of reverse-biased p-n junctions. The quasi-Fermi levels for forward-biased p-n junctions are generally displayed correctly. Fig. 1 shows a few representative band diagrams from well-respected textbooks where the quasi-Fermi levels of reverse-biased pn junctions extend into the conduction and valence bands. Is this possible?

The quasi-Fermi levels are defined through the following:

$$n=n_i \exp\left[(E_{\mathrm{Fn}}-E_i)/kT\right]; p=n_i \exp\left[-(E_{\mathrm{Fp}}-E_i)/kT\right] \quad (1)$$

which lead to

$$E_{\mathrm{Fn}} = E_i + kT\ln(n/n_i); E_{\mathrm{Fp}} = E_i - kT\ln(p/n_i). \quad (2)$$

To determine E_{Fn} and E_{Fp}, we need the electron and hole densities. To get the main points across, we will confine ourselves to simple calculations. To determine n and p, we start with the reverse-bias leakage current density, i.e.,

$$J_{\mathrm{leak}} = \frac{qn_iW}{\tau_g} = qnv \quad (3)$$

with W as the space-charge region width, τ_g as the generation lifetime, and v as the electron velocity. We will consider a reverse-biased Si p$^+$-n junction with $n_i = 10^{10}$ cm^{-3} and $\tau_g =$ 10 ms, which is a representative of a high-quality Si diode. These values lead to $J_{\mathrm{leak}} = 3 \times 10^{-11}$ A/cm^2 for $W = 2$ μm. Leakage current densities of this magnitude and even lower are common for today's charge-coupled devices and CMOS imagers. With these parameters and $v = 10^7$ cm/s

$$n = \frac{n_iW}{\tau_g v} = 20 \text{ cm}^{-3}. \quad (4)$$

Taking p = n for simplicity, which is reasonable in a reverse-biased space-charge region, leads to

$$E_{\mathrm{Fn}} = E_i - 0.52; E_{\mathrm{Fp}} = E_i + 0.52 \text{ eV} \quad (5)$$

at room temperature. These values show the quasi-Fermi levels to lie within the band gap, albeit close to conduction and valence bands, as shown in Fig. 2(a) and contrary to Fig. 1. As an aside, for the quasi-Fermi levels to lie *within* the bands by as much as 1 eV in Fig. 1 requires n and p to be $\sim 3 \times 10^{-9}$ cm^{-3}, which is most unlikely a low value.

We simulated p$^+$-n junctions in 2-D. The resultant band diagram is shown in Fig. 2(b). The p-type doping concentration is 10^{18} cm^{-3}, and the n-type doping concentration is 10^{16} cm^{-3}; both p and n sections are 1 μm wide. All contacts are ohmic contacts. To see if our "back of the envelope" calculations are correct, we simulated the band diagram using Silvaco. The simulated band diagram in Fig. 2(b) shows good agreement with the simple calculations.

Having clarified the location of the quasi-Fermi levels in p-n junctions, the next step is to determine the quasi-Fermi levels in MOSFETs. These are more complex than in p-n junctions and are rarely shown in textbooks or papers. The first question: what is the channel electron concentration, n? We need this to get a first estimate of the electron quasi-Fermi level. To first order, the electron densities n_s (#/cm^2) and n (#/cm^3) are

$$n_s = C_{\mathrm{ox}}(V_G - V_T)/q; n = n_s/t_{\mathrm{ch}}. \quad (6)$$

For $t_{\mathrm{ox}} = 2$ nm and $V_G - V_T = 1$ V, we get $n_s = 10^{13}$ cm^{-2}. Although the channel shape in the vertical direction is

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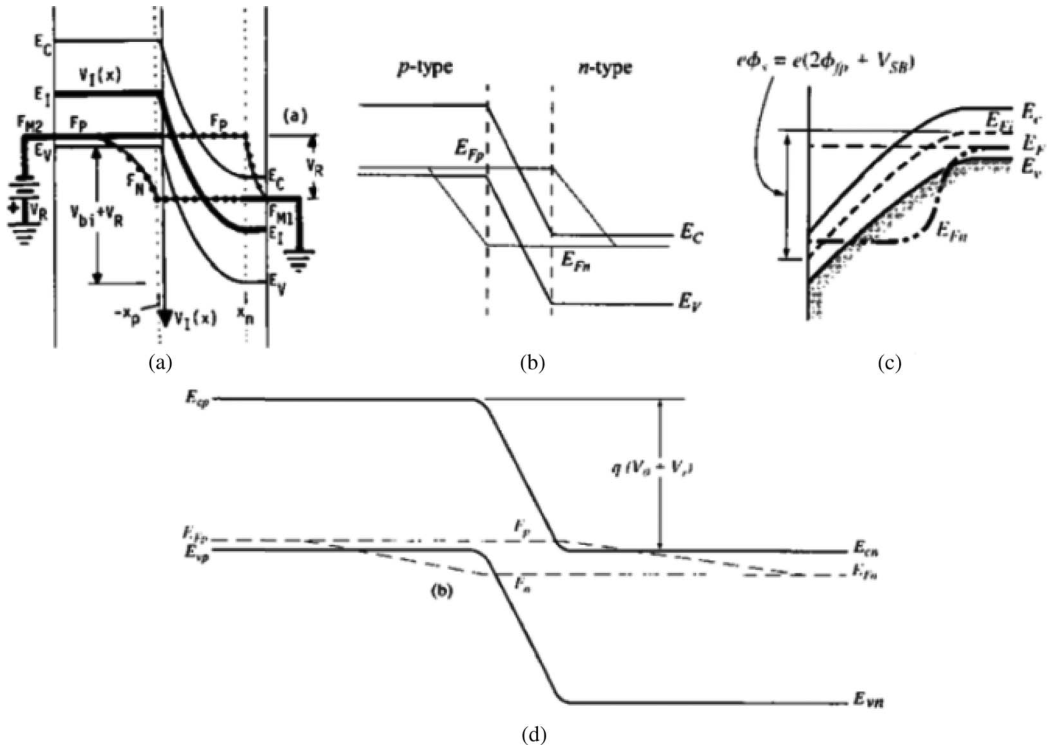


Fig. 1. Band diagrams of reverse-biased p-n junctions taken from: (a) [1], (b) [2], (c) [3], and (d) [4].

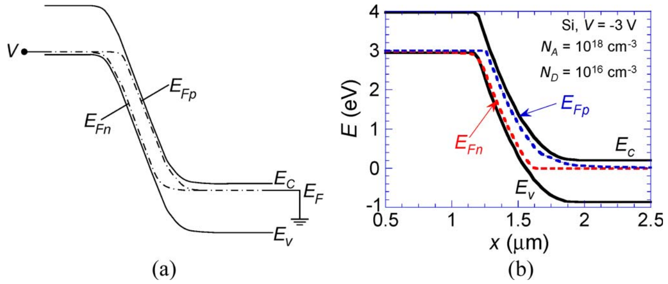


Fig. 2. Band diagrams of p$^+$-n junction (a) with simple equation, and (b) simulation. $N_A = 10^{18}$ cm^{-3}, $N_D = 10^{16}$ cm^{-3}, $V = -3$ V.

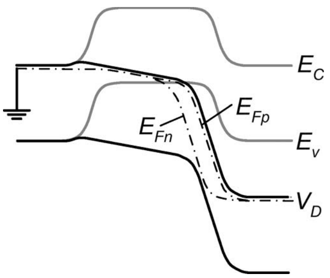


Fig. 3. MOSFET band diagram for $V_D = 0$ and $V_D > 0$ based on simple calculations.

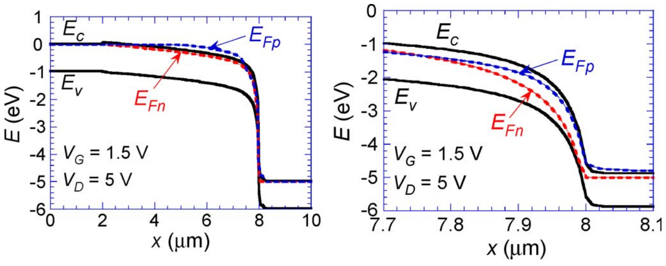


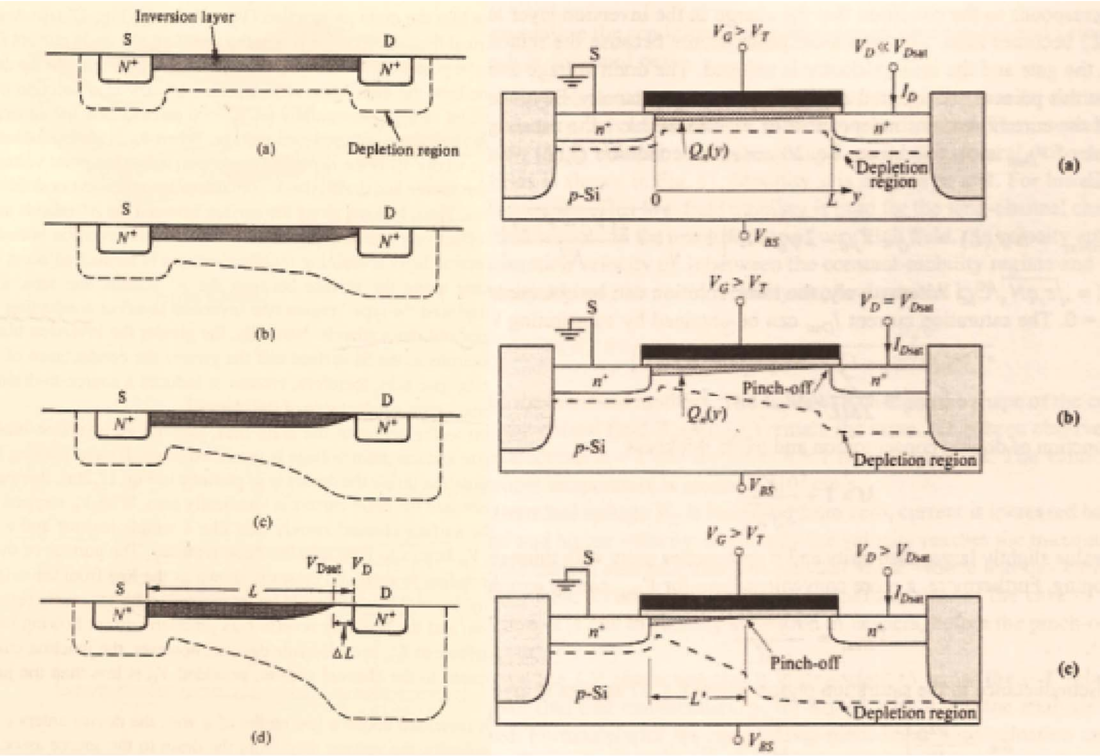
Fig. 4. Simulated MOSFET band diagrams.

complicated, we assume a channel thickness of 10 nm leading to $n = 10^{19}$ cm^{-3}. From (2), the electron quasi-Fermi level is $E_i + 0.53$ eV, i.e., it lies close to the conduction band, as one would expect. In the channel near the source, the device is close to equilibrium, and the hole density is approximately $p \approx n_i^2/n = 10$ cm^{-3}, leading $E_{\mathrm{Fn}} \approx E_{\mathrm{Fp}}$. As the channel approaches the drain, the reverse bias there splits the quasi-Fermi levels much as in reverse-biased p-n junctions. Hence, our band diagram, based on these simple first-order considerations, is shown in Fig. 3. The faint conduction/valence bands refer to $V_D = 0$ and the solid ones to $V_D > 0$.

To see what the band diagram actually looks like, we simulated the MOSFET and show the results in Fig. 4. The quasi-Fermi levels actually split in the channel slightly beyond the source. They split further along the channel with E_{Fp} moving slightly into the conduction band and in the reverse-biased space-charge region near the drain; the quasi-Fermi levels are similar to those in reverse-biased junctions.

III. MOSFET CHANNEL SHAPE

Our second topic deals with the MOSFET channel shape depicted in some textbooks, shown in Fig. 5. What lead us to these considerations is the following. Consider the MOSFET in Fig. 6(a). For $V_G > V_T$, a channel is formed between the source and the drain. With $V_D = 0$, the channel is obviously

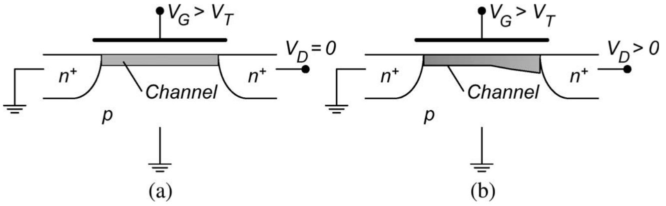


(a) (b)

Fig. 5. MOSFET cross sections from (a) [6] and (b) [2].

uniformly thick along its entire length because the vertical gate-induced electric field is uniform. However, for $V_D > 0$, the vertical electric field near the grounded source is clearly higher than near the positively biased drain, and when $V_D \Rightarrow V_G$, then the vertical electric field near the drain vanishes entirely, and there is no longer any field to force the channel electrons against the $\mathrm{SiO_2/Si}$ interface. Instead, the channel should broaden, illustrated in Fig. 6(b). However, the channel is frequently shown to become thinner and to vanish at the pinchoff point. Perhaps, the authors mean to show the channel density to decrease toward the drain, but the cross sections appear to indicate the channel to vanish. The explanations are: "... the channel eventually reaches a point at which the inversion charge at the drain is reduced to zero, called the pinchoff point." [2] The term "pinchoff" appears to have been used first by Shockley when discussing junction FETs (JFETs), who says: "W_o is the magnitude of reverse bias required to make the space charge penetrate the entire p-region. We shall refer to it as the "pinchoff voltage" since it is the voltage that will reduce the channel to zero and pinch off the conducting path between terminals 1 and 2." [5] These comments were made for JFETs and not MOSFETs. However, the term pinchoff has been has been carried into MOSFET literature in papers and books.

We simulated MOSFETs in 2-D structures. The substrate is p-type, the substrate doping concentration is 10^{16} cm^{-3}, and the geometry is defined as 10 μm long and 5 μm deep. The source and the drain are n-type with the doping concentration of 10^{19} cm^{-3}, 2 μm long, and 2 μm deep, which are implanted into the substrate at the upper left and right corners. A 10-nm-thick gate oxide on the upper surface of the substrate between the source and the drain has some overlap over the source and the drain. All gate, source, drain, and substrate contacts are ohmic contacts.

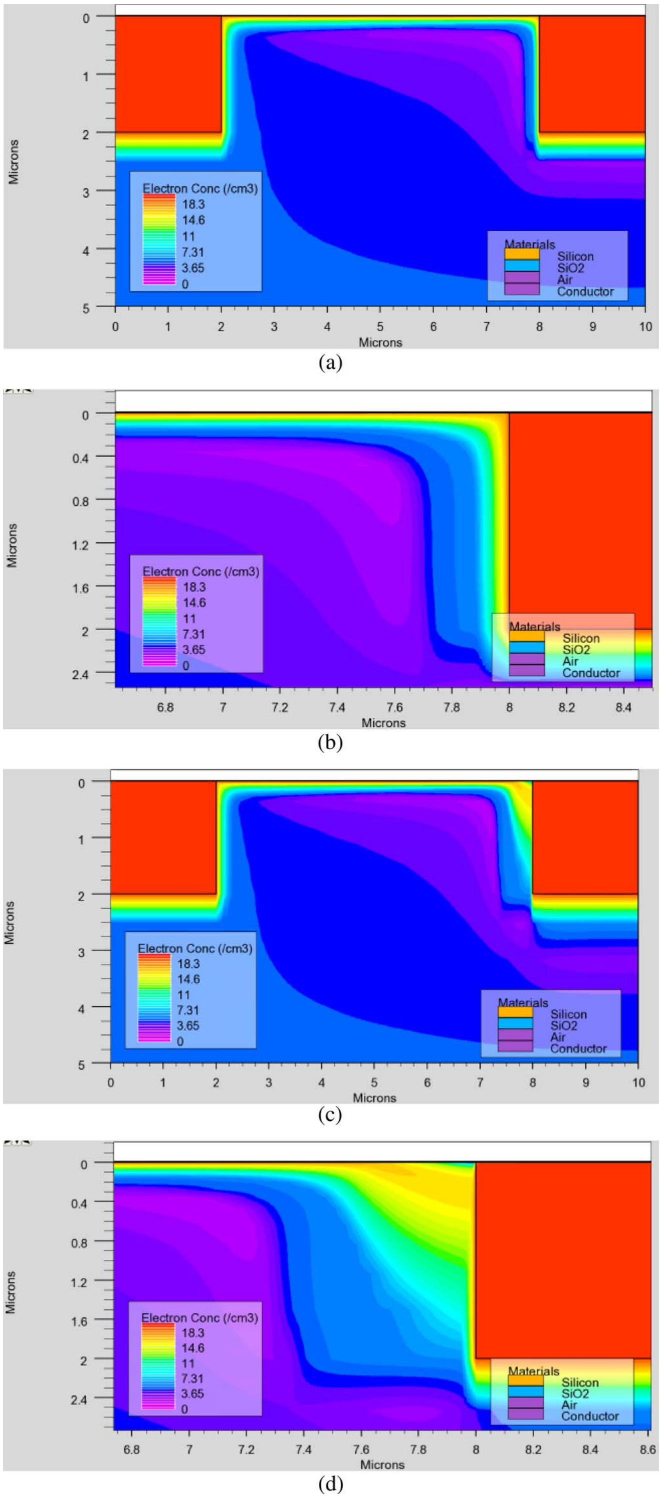


(a) (b)

Fig. 6. Schematic MOSFET cross sections for $V_D = 0$ and $V_D > 0$, showing the channel shape with the channel becoming thicker near the drain.

To see if our ideas are correct, the MOSFET results are shown in Fig. 7. Fig. 7(a) shows the channel for $V_G = 1.5$ V and $V_D = 1$ V. The channel is reasonably uniform, but its thickness increases slightly near the drain as shown in the enlargement in Fig. 7(b). As the drain voltage is increased to 5 V, the channel thickening becomes very obvious in Fig. 7(c) and (d).

It is clear that before pinchoff, the channel thickness remains reasonably constant from the source to the drain. The closer the channel is to the $\mathrm{SiO_2/Si}$ interface, the higher the electron concentration, as shown in Fig. 7; the electron concentration decreases in the vertical direction as expected. However, after pinchoff, the channel shape approaches a triangular shape toward the drain; the electron concentration spreads out from the pinchoff point to the drain. In the triangular region, the electron concentration peak is no longer close to the $\mathrm{SiO_2/Si}$ interface, as shown in Fig. 7(c), with the electron concentration peak region bending down as it approaches the drain. Then, the



(a)

(b)

(c)

(d)

Fig. 7. Simulated MOSFET cross sections for various drain voltages. (a) Before pinchoff, $V_G = 1.5$ V, $V_D = 1$ V. (b) Pinchoff region before pinchoff. (c) After pinchoff, $V_G = 1.5$ V, and $V_D = 5$ V. (d) Pinchoff region after pinchoff.

electron concentration above the peak region decreases rapidly and forms a low electron concentration triangular area at the corner next to the drain in Fig. 7(d).

IV. SUMMARY

We have addressed quasi-Fermi levels and MOSFET channel shape in this brief. We did this because these two are frequently misrepresented in published papers and books. Through simple first-order calculations and detailed computer simulations, we show that the quasi-Fermi levels in reverse-biased junctions lie inside the energy gap, rather than in the conduction and valence bands as frequently portrayed. MOSFET channels are also frequently misrepresented as "disappearing" near the drain, contrary to what actually happens in the channel. The channel actually expands from the source to the drain rather than pinching off at the pinchoff point and disappearing after the pinchoff point. After the pinchoff point, the channel broadens because the vertical electric field decreases, and the current spreads out as it approaches the drain. We hope that these calculations/simulations/figures will clarify these concepts for the reader.

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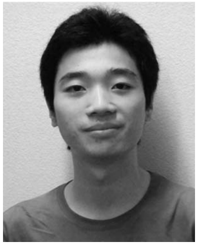

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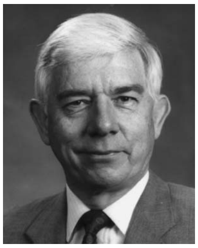

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