On the 60 mV/dec @300 K Limit for MOSFET Subthreshold Swing

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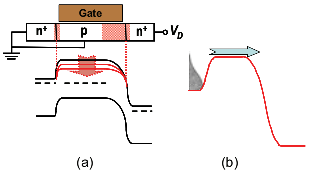
***Abstract*— The 60 mV/dec limit for subthreshold swing at 300 K is generally considered a fundamental limit that cannot be defeated. The physical origin of this limit is revisited in this paper and the fact that this limit is in part determined by the density-of-states (DOS) of the source is highlighted. A scheme of engineering this DOS is proposed as a possible way to achieve subthreshold swing much lower than the 60 mV/dec value.**

INTRODUCTION Power dissipation is the true brick wall in front of the IC technology's relentless march toward an ever higher level of integration [1]. Both static and dynamic power dissipation are contributing to this crisis. Dynamic power is well known to be proportional to CfV^2, where C is the load capacitance, f is the clock frequency, and V is the supply voltage. This is the primary reason the clock speed of advanced microprocessors no longer increases. Static power is off-state leakage that mainly consists of two parts; subthreshold leakage and the gate leakage. A huge effort is currently being applied toward developing high-k gate dielectrics to head off the gate leakage problem. Thus the subthreshold leakage is the most important static power problem. To solve the power dissipation problem, it is clear that one needs to lower the operation voltage while keeping the subthreshold leakage very low. This is an unbridgeable brick wall because of the finite value of the subthreshold swing – or the sharpness of the ON/OFF switching. A big part of advanced IC technology development is to achieve the best gate control of the channel to minimize the subthreshold swing degradation from the ideal value. However, it is generally accepted that the best one can do is to reach the theoretical limit of 60 mV/dec @300 K.

Power dissipation is such an important problem that there has always been strong interest in seeking ways to make the subthreshold swing smaller. Since the 60 mV/dec is generally considered a fundamental limit for field-effect-transistors, the only option is to introduce additional current-controlling mechanisms such as tunneling [2] and impact ionization [3]. These approaches have so far been not very successful, although some recent ideas seem more promising [4].

In this paper, the origin of the 60 mV/dec limit is revisited. Note the word revisited is used here. Most reader will feel that they know about this all along because this is how the subject was taught when they took device physics course. Nevertheless, the wide-spread referral of the 60 mV/dec as fundamental limit warrants a revisit of this simple fact of device physics. Once we reaffirmed that the limit is not a fundamental one, we can examine the possibility of achieving a much smaller subthreshold swing without additional controlling mechanisms is also discussed.

THE "LIMIT" Consider the basics of MOSFET operation. Figure 1a shows the band diagram of an n-channel MOSFET. A leakage (diffusion) current flows from source to drain. As gate voltage is applied, the barrier for majority carrier diffusion from source to drain is reduced. The lower the barrier, the higher is the diffusion current. This is the aforementioned subthreshold leakage. Figure 1b illustrates the electron density as a function of energy at the source electrode. As the barrier for diffusion is lowered, the density of electrons that have energy above the barrier increases exponentially, driving up the leakage current. This electron energy distribution is the fundamental physics that results in the 60 mV/dec value.



(a) (b)

Fig. 1. (a): Band diagram of an n-channel MOSFET illustrating the gate controlled lowering of the diffusion barrier from source to drain. (b): Illustration of the exponential decay of electron density as a function of increasing energy.

The electron energy distribution is a product of two terms, the Fermi-Dirac distribution and the electron density of states (DOS). As long as we are dealing with electrons, we cannot escape the Fermi-Dirac distribution. For most materials, the DOS is a slowly and monotonically increasing function roughly approximated by: $g_C(E) = 4\pi\left(\frac{2m_n^*}{h^2}\right)^{3/2}(E-E_C)^{1/2}$.

It is the product of the DOS and the Fermi-Dirac distribution function:

$$f(E) = \frac{1}{1+\exp\left[\frac{E-E_F}{kT}\right]}$$

That gives rise to the familiar relationship of

$$n \approx N_C e^{-(E_C-E_F)/kT},$$

where m_n^* is the electron effective mass, h is the Plank's constant, E_C is the conduction band edge, N_C is the effective density of states, E_F is the Fermi energy, k is the Boltzmann constant, and T is temperature in Kevin. This most common case is illustrated in figure 2a.

This means that electron density decreases exponentially with increasing energy, leading to the simple relationship for subthreshold swing:

$$S(T) \approx \ln(10)\cdot\frac{kT}{q},$$

or ~60 mV/dec at 300 K. Thus, as long as we are dealing with pn junctions, we have the 60 mV/dec as the fundamental limit for MOSFET subthreshold swing.

BREAKING THE LIMIT The monotonically increasing functional description of DOS is valid for most materials with a wide partly filled band. However, some materials such as transition metals have sharp partly filled bands due to the d-orbital. For example, the DOS for Ni [5] is shown in figure 3.

Notice that the Fermi level is at the lower half of the d-band, meaning that the DOS is rising rapidly while the occupancy probability is dropping rapidly as illustrated in figure 2b. The DOS soon peaked and start to drop rapidly. The product of this drop and the fast decreasing occupancy probability leads to a decrease in electron density must faster than exponential as electron energy increases. From the right side of figure 2b, we show that the threshold can be set lower without diffusion current leakage. When the barrier is lowered further, the current rises much faster than exponential, leading to a subthreshold swing substantially less than 60 mV/dec as shown in figure 4 (dotted red line).

Fig. 2 Left: Solid red line represents Density of state (DOS); Dotted pink line represents the Fermi level; Borken black line represent the probability of state being vacnant (Fermi-Dirac function); Shaded area represents the electron energy distribution. Right: Shaded area represents the electron energy distribution; Solid blue line represents the band diagram across the MOSFET channel. (a) Wide energy band of common material near the bottom of the conduction band leading to an exponential decay in electron density as energy increase. (b) The sharp d-band of Ni with the Fermi level at the lower half og the band. The electron density decreases much faster than exponential as energy increases. (c): Using work function engineering, the Fermi level can be pushed to the top half of the d-band, resulting in a even faster decay in electron density as energy increases.

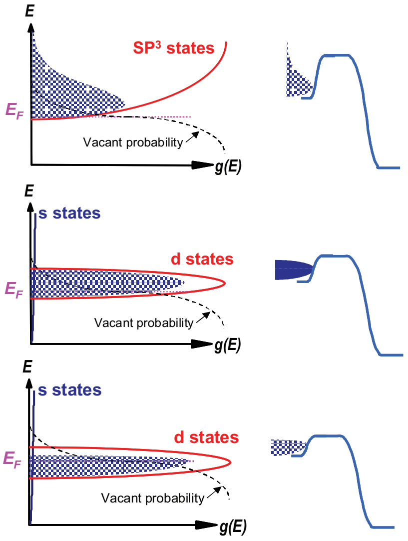
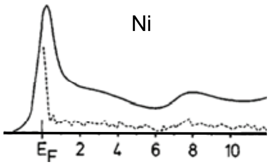
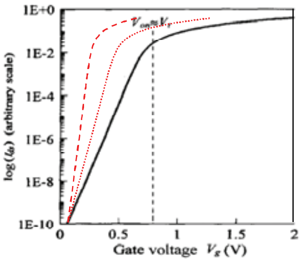


Fig. 3: Density of state for Nickel showing the sharp d-band. Solid line: Photemission spectrum. Broken line: Spectrum when instrument broadening is removed. Extracted from Ortega *et al.* Phys. Rev. B, **47**, 16441(1993).



To take advantage of the d-band characteristics of Ni to achieve steeper subthreshold swing for MOSFET, Ni must be used as the source material in direct contact with the channel. This means a Schottky junction at the source. Not only that, the interface must be so good that the DOS remains similar to that of the bulk. Exactly how the DOS change at and near the interface is a poorly studied subject. What is proposed here may or may not be possible.

Fig. 4: I_D-V_G characteristics of an n-channel MOSFET showing the conventional subthreshold swing near the 60 mV/dec limit (solid black line), the subthreshold swing with shape d-band metal as source material (red dotted line), and the subthreshold swing of the same d-band metal source with work function engineering to push the Fermi level into the upper half of the band (broken red line).



Assuming that one can maintain the DOS structure at the interface, the performance of the device, in terms of steep subthreshold swing, can be improved further by work function engineering. Various methods have been introduced in recent years to engineer the work function of the gate electrode to achieve low threshold operation in advanced MOSFET. It can be as simple as using another layer of metal to adjust the Fermi level of the metal of interest [7]. If we use such method to raise the Fermi level of NI to the upper half of the d-band as shown in figure 2c, we can sharpen the decay in electron density as the electron energy increase. This will result in a even steeper subthreshold swing as shown in figure 4 (broken red line).

Using a Schottky contact and needing to maintain the DOS all the way to the interface are obviously the main obstacles in the way of realizing the proposed steep subthreshold MOSFET. Schottky source/drain for MOSFET is an idea that existed for over four decades [6]. Theoretically, the Schottky S/D transistor should have better performance than conventional transistors, although fabrication difficulty has so far prevented this from being realized (in manufacturing). With Schottky S/D technology, a wide variety of metal can be used. So far, all the efforts have been focused on engineering the Schottky barrier height. This does not have to be the case. Choosing the right metal not only with the correct Schottky barrier height, but also the correct DOS can achieve subthreshold swing that is well below the 60 mV/dec limit.

Schottky S/D technology is challenging, but the need to solve the series resistance problem is already driving its development. To achieve steep subthreshold swing, there are additional material issues. Ni, for example, will not be suitable for nMOSFETs because the Schottky barrier will be too high. Its work function is more suitable for pMOSFETs. Recent advances in work function engineering [7-10] suggest that we can manipulate the Fermi level.

Several transition metals have the sharp d-band, so material choices are not too limited. However, the interface is not a well understood region. We do not know, for example, what the DOS looks like at the interface. It may or may not resemble the bulk DOS. Theoretical understanding is weak in this aspect. Nevertheless, the possibility of success is there.

CONCLUSIONS The common conception that 60 mV/dec is a fundamental limit for subthreshold swing of MOSFETs is not correct. It is a limit only for the materials commonly found in the source and drain of MOSFETs. Replacing the source material with materials that has a sharply decreasing DOS can result in a subthreshold swing significantly below the 60 mV/dec value. This opens up new possibilities in ultra low power electronics.

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