Fundamental Tradeoff between Conductance and Subthreshold Swing Voltage for Barrier Thickness Modulation in Tunnel Field Effect Transistors

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Fundamental Tradeoff between Conductance and Subthreshold Swing Voltage for Barrier Thickness Modulation in Tunnel Field Effect Transistors

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There is a fundamental tradeoff between conductance and subthreshold swing voltage in tunnel field effect transistors that achieve a sharp turn off by modulating the tunnel barrier thickness. At high conductivities, the voltage bias has little control over the tunneling probability. Unfortunately, this results in a poor subthreshold swing voltage at high conductivities. In tunnel field effect transistors, the best sub 60mV/decade results occur only at very low current densities around 1nA/μm. At higher current densities the subthreshold swing voltage is observed to be much worse than 60mV/decade. We show that this is an inherent problem in quantum barrier thickness modulation, and that a different mechanism, band-edge energy filtering, is needed.

The operating voltage of conventional MOSFETs is fundamentally limited to the thermal subthreshold swing voltage or Boltzmann limit, 60mV/decade. Tunnel field effect transistors promise to overcome the Boltzmann limit, by invoking a different electrical switching mechanism[1-3]. There are two alternative switching processes that can be used to supersede Boltzmann switching.

The band edge energy filtering or band overlap mechanism is illustrated in Fig. 1. If the conduction and valence bands do not overlap, no current can flow. Once they do overlap, there is an energy overlap for current to flow. Since there are states below the band edge, the turn on will reflect the band edge density of states.[4]

Alternatively, we can obtain a steep turn on by using the gate voltage to modulate the tunnel barrier thickness, changing the tunneling probability as shown in Fig 2. In this regime, the tunneling barrier will become thicker and block off the tunneling current.

Many of the best experimental results rely on modulating the tunnel barrier thickness[5-9]. Consequently, the subthreshold swing voltage is steeper than 60 mV/decade only at a low current density of ~1nA/μm. We will prove that this is due to a fundamental tradeoff between the subthreshold swing voltage and conductance for the tunnel barrier thickness modulation mechanism. At high conductivities voltage bias cannot control the barrier width effectively, resulting in a poor subthreshold swing voltage.

To estimate how steep the subthreshold swing voltage can be under Barrier Thickness Modulation, we first consider the tunnel probability, $\mathcal{T}$, for a triangular barrier, as expected in a switching device[10]:

$$\mathcal{T}(\vec{F}) = \exp\left(\frac{-4\sqrt{2}(m^*_{tunnel})^{1/2}E_G^{3/2}}{3\hbar q|F|}\right) \equiv \exp\left(\frac{-\alpha}{|F|}\right) \quad (1)$$

The electric field across the junction is given by F, the effective mass for tunneling is m^*_{tunnel}, and E_G is the band gap. All of the parameters can be collected into a single constant, α. Regardless of the exact shape of the barrier, there will generally be a constant α such that $\mathcal{T}=\exp(-\alpha/F)$ where F is now the peak electric field.. Such a constant, α, can even be defined for most heterojunctions.

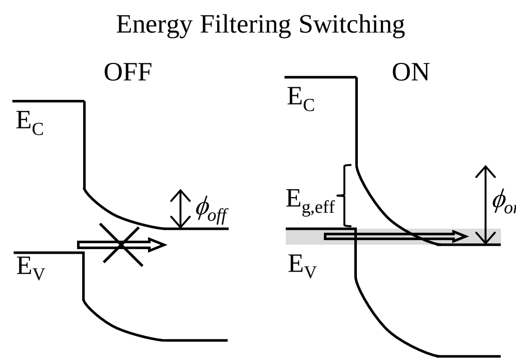

Fig. 1: Applying a bias changes the band alignment. When the conduction and valence band don't align, no current can flow. Once they align, current can flow. Either a heterojunction or a homojunction can be used. A type II heterojunction is shown to allow for a smaller effective tunneling barrier height, $E_{g,eff}$.

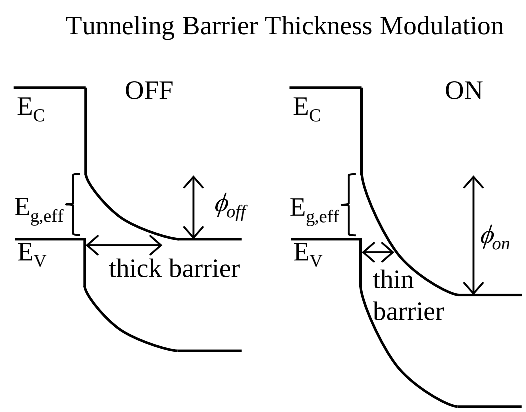

Fig. 2: Applying a bias changes the thickness of the tunnel barrier and thus the tunneling current.

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To find the subthreshold swing voltage, we need to specify the on-state conductance, and off-state conductance, and then determine the voltage required to switch On/Off. The systems viewpoint requires ~1mS/μm in the On-state, and ~1nS/μm in the Off-state, which specifies $\mathcal{T}_{on}$ and $\mathcal{T}_{off}$ respectively. The effective subthreshold swing voltage from barrier width modulation is defined as:

$$\langle S_{tunnel} \rangle \equiv \frac{\phi_{on} - \phi_{off}}{\log(\mathcal{T}_{on}/\mathcal{T}_{off})} \tag{2}$$

$\langle S_{tunnel} \rangle$ is the steepness in mV/decade resulting from tunnel barrier thickness modulation. The potential across the tunneling barrier in the on and off states is given by ϕ_{on} and ϕ_{off}, respectively, as shown in Fig. 2. The difference, $\phi_{on} - \phi_{off}$, is equal to the minimum voltage required to switch the device, assuming perfect gate control. Eq. (2) indicates the best subthreshold swing that can be achieved using barrier thickness modulation.

The electric field is proportional to the potential across the junction, $F=\phi/l_o$. We will consider different electric field profiles later. Using Eq. (1) we can relate the tunneling probability to this potential across the tunneling junction:

$$\mathcal{T} = \exp\left(\frac{-\alpha}{F}\right) = \exp\left(\frac{-\alpha}{\phi/l_o}\right) \tag{3}$$

We can invert Eq. (3) for a specific on-state, with ϕ_{on} and $\mathcal{T}_{on}$:

$$-\alpha \times l_o = \ln(\mathcal{T}_{on}) \times \phi_{on} \tag{4}$$

The equation for the Off-state corresponding to Eq. (3) is:

$$\mathcal{T}_{off} = \exp\left(\frac{-\alpha \times l_o}{\phi_{off}}\right) = \exp\left(\frac{\ln(\mathcal{T}_{on}) \times \phi_{on}}{\phi_{off}}\right) \tag{5}$$

where Eq. (4) is inserted for $\alpha \times l_o$. Now solving for ϕ_{on} gives:

$$\phi_{on} = \phi_{off} \frac{\ln(\mathcal{T}_{off})}{\ln(\mathcal{T}_{on})} = \phi_{off} \frac{\log(\mathcal{T}_{off})}{\log(\mathcal{T}_{on})} \tag{6}$$

Thus we have the potential across the tunneling barrier in the On-state, given a certain on/off ratio, and given the Off-state potential. This allows us to find the total voltage swing required to turn the junction on and off:

$$\Delta\phi = \phi_{on} - \phi_{off} = \phi_{off}\left(\frac{\log(\mathcal{T}_{off})}{\log(\mathcal{T}_{on})} - 1\right) \tag{7}$$

We insert this back into Eq. (2), the subthreshold swing voltage, to obtain:

$$\langle S_{tunnel} \rangle = \frac{\phi_{off}\left(\frac{\log(\mathcal{T}_{off})}{\log(\mathcal{T}_{on})} - \frac{\log(\mathcal{T}_{on})}{\log(\mathcal{T}_{on})}\right)}{\log(\mathcal{T}_{on}) - \log(\mathcal{T}_{off})} = \frac{\phi_{off}}{-\log(\mathcal{T}_{on})} \tag{8}$$

The final result on the right hand side is intentionally expressed in terms of the minimal number of design parameters, ϕ_{off} and $\mathcal{T}_{on}$. For a high on-state conductance around 1mS/μm, a reasonable value of the tunnel probability should typically be at least 1%, $\mathcal{T}_{on} = 10^{-2}$. This implies $\langle S_{tunnel} \rangle = \phi_{off}/2$, or for a higher $\mathcal{T}_{on} = 10^{-1}$, $\langle S_{tunnel} \rangle = \phi_{off}$. A subthreshold swing voltage $\langle S_{tunnel} \rangle$=60mV/decade, demands ϕ_{off}<120mV, for a 1% tunneling probability. This ϕ_{off} is unreasonably small and conflicts with a low Off-state current, which would require a larger ϕ_{off} potential barrier, as we will show later.

It is helpful to consider the subthreshold swing voltage defined locally at a single current point, to see how it varies with current. At a single point we consider the limit where $\phi_{off} \to \phi_{on} \equiv \phi$, and $\mathcal{T}_{off} \to \mathcal{T}_{on} \equiv \mathcal{T}$. Consequently, Eq. (8) becomes:

$$S_{tunnel} = \frac{\phi}{-\log(\mathcal{T})} \tag{9}$$

As we can see from Eq. (9), the lower the tunneling probability, the steeper the subthreshold swing voltage. In all of the steep experimental results, the subthreshold swing gets worse as the tunneling probability, $\mathcal{T}$, increases and follows the trend indicated by Eq. (9). Since the steepness gets worse at high tunnel probability or higher currents, a steep subthreshold swing voltage at low currents is insufficient for making a practical logic switch. The conflict between subthreshold swing and good tunneling current, is inherent for the barrier thickness modulation mechanism. Eq. (9) is likely to account for the steep subthreshold swing voltages that have been experimentally measured, all at extremely low current densities[5-9].

It would seem that Eq's. (8)&(9) have proven that tunnel barrier modulation *cannot* simultaneously provide steepness and a high current density. There remains the possibility of that ϕ_{off} might be allowed to be small and to rely on a large tunnel barrier thickness to shut-off the current. Therefore, we need to ask what is the lowest off-state potential, ϕ_{off} that is reasonable?

In barrier thickness modulation, the bands must be overlapped, otherwise the band edge energy filtering mechanism would also cut off the current. The Off-state must already be present when the bands are just starting to overlap. Therefore, The available Off-state potential ϕ_{off} will be equal to the band gap of a homojunction or the effective tunneling barrier height, $E_{g,eff}$, in a heterojunction, as shown in Fig. 2(a).

Now that we know $q \times \phi_{off} = E_{g,eff}$, we can evaluate the subthreshold swing voltage due to barrier width modulation, S_{tunnel}, for different semiconductors: Even for the very small bandgap, $E_{g,eff}$ =0.35eV of InAs, $\langle S_{tunnel} \rangle$= 177 mV/decade for $\mathcal{T}_{on}$ =1%, as seen from Eq. (8). This voltage swing is worse than the 60 mV/decade Boltzmann limited swing. Clearly, at high current densities, barrier thickness modulation in a homojunction will not give a subthreshold swing voltage steeper than 60 mV/decade.

A smaller effective barrier height can be achieved using a Type II hetero-junction as shown in Fig. 2. For a reasonable 1% tunneling probability, Eq. (8) requires that $E_{g,eff} = q \times \phi_{off}$ must be less than 120 meV to do better than the Boltzmann limit. In principle this could be achieved by

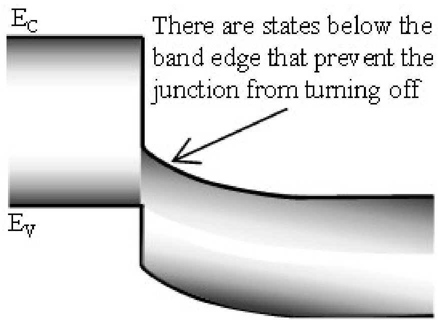

Fig. 3: If the effective band gap is too small, there are band tails below the band edge that can prevent the junction from turning off. The band tail density of states is indicated by the shaded regions. In this case the steepness is controlled by the energy filtering mechanism.

using a small height, but thick, tunneling barrier. Unfortunately, band-tail states prevent the small height barrier from effectively blocking the current[4, 11, 12]. This is illustrated in Fig. 3. Electrons tunnel into the band tails instead of being blocked by the barrier, spoiling the Off-state.

We now quantify, the degree to which the small height, but thick, tunneling barrier mechanism is ineffective. The band-edge density of states typically falls of exponentially below the band edge as seen in the Urbach tail of optical absorption measurements[4, 12]. We can parameterize this fall off with the term S_{DOS} which represents how many millivolts you need to go below the band edge to reduce the joint conduction/valence band density of states by a decade.[4] To ensure a particular On/Off ratio, the employed barrier height, $E_{g,eff}$, must be large enough to suppress the band edge density of states, S_{DOS}, by that On/Off ratio. Consequently, we arrive at the following limit:

$$q \times S_{DOS} < \frac{E_{g,eff}}{\log(I_{on}/I_{off})} \tag{10}$$

To use tunneling barrier width modulation at high current densities we need an Off-state barrier height $E_{g,eff}$ <120 meV. In addition, for six decades of On/Off ratio, S_{DOS} must be steeper than 120/6 = 20 mV/decade, a material sharpness which has never been achieved electrically[4].

If such a steep band-tail material were to be found, the steepest turn on would come from band edge energy filtering rather than the tunnel barrier thickness modulation. Unavoidably, at small effective bandgap, where tunnel probability could possibly have a steep and sensitive response, that response will be controlled by a different mechanism, namely energy filtering at the band-tails. Consequently, modulating the thickness of the tunneling barrier will not give a steep subthreshold swing at high current densities, even with the small height, but thick, tunneling barrier.

In the previous analysis of barrier thickness modulation we have assumed that the electric field is proportional to the potential across the junction: $F=\phi/l_o$. This directly corresponds to the proposed bilayer TFET[13, 14]. The same model is true for the peak electric field in a MOSFET channel where the voltage typically decays exponentially and is set by a screening length, l_o:

$$V(x) = \phi\left(1 - e^{-x/l_o}\right) \tag{11}$$

The position along the channel is given by x, and the peak field occurs at x=0. This results in:

$$\vec{F}(x=0) = -\left.\frac{dV}{dx}\right|_{x=0} = \frac{-\phi}{l_o} \tag{12}$$

For a doped pn-junction, such as a typical tunnel diode, the potential will be parabolic and so the peak electric field will be proportional to the square root of the potential: $F \propto \sqrt{\phi}$. Rederiving Eq's. (2)-(8) leads to:

$$\langle S_{tunnel} \rangle \geq \frac{2 \times \phi_{off}}{-\log(\mathrm{T}_{on})} \tag{13}$$

which is twice as bad as the linear potential, Eq. (8)

We have proven that tunnel barrier modulation alone *cannot* simultaneously provide steepness and a high current density. Good experimental results at very low currents do not promise steep subthreshold swings at high current densities. Instead, at high current densities, a different mechanism, bandedge energy filtering is needed. Therefore the emphasis must be placed on measuring, understanding, and engineering of the bandedge joint density of states.

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