Ballistic Transport in Nitride Devices

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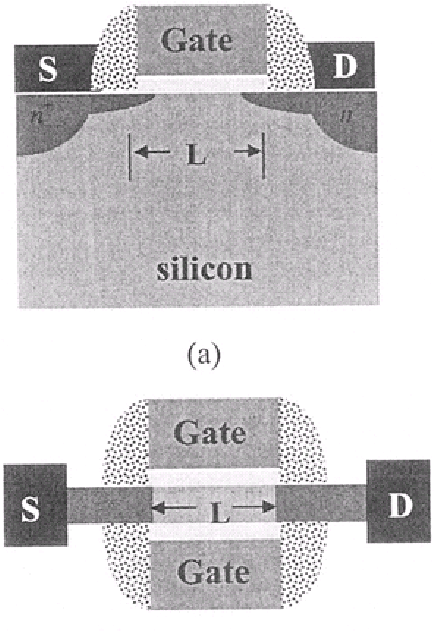
Silicon MOSFET technology has been developed for about 50 years. The initial channel lengths in the 1960's were about 10 micrometers. To push MOSFETs to the limit of performance, now researchers are trying to build devices with the channel length a thousand times shorter, which is less than 10 nanometers. Electrons in the traditional semiconductor transistors normally suffer from various scattering since the mean free path of electrons is in nano scale, which is much less than the channel length. However, in the nanoscaled transistors, electrons may live in the ballistic transport regime and travel from source to drain without being scattered. Therefore the electron velocity can be much higher compared to that in the traditional transistors. This leads to a higher current-carrying capability.

Consider the discrete doping effect in silicon-based MOSFETs, which is the fundamental limit of the channel length, to develop field effect transistors (FETs) without using dopants is important for future nano-scaled devices. Heterojunctions based on nitride material provide polarization induced two dimensional electron gas (2DEG) which is dopant-free and never freeze under low temperature. Traditional nitride based high mobility electron transistors (HEMTs) have been widely used for military use like radar and civil use like high power switching, Nitride based HEMT is promising to be further developed to work in or very close to the ballistic transport regime. Such nano-scale HEMT is a good candidate for next generation FETs and can be used in the extreme environment like outer space.

In this study, we are going to review the theory developed for ballistic silicon MOSFET. The ideal ballistic model of MOSFET will be introduced. We will also study the transport in FETs close to the ballistic regime, where the channel is not short enough and scattering still exists.

Fig 1 (a) shows the cross section for a bulk silicon MOSFET. Considering the simplicity from a symmetric layout, the double-gate MOSFET as shown in Fig (b) is treated. In the channel, If only the ground subband is occupied by electrons, E-k diagram can be related directly with the current in the channel as Fig 2 shows. In the plot, source is on the left and drain is on the right. From source to drain, the material is n+-silicon, p-silicon and n+-silicon. A barrier is formed in the middle of the conduction band. Any electrons traveling from source to drain have to overcome this barrier. E-k diagram is studied at the top of the barrier. This position provides following three properties: 1. carrier distribution function at the barrier top consists of two thermal equilibrium halves, from source and from drain; 2. for an electrostatically well-designed MOSFET, the total carrier density at the barrier top is about a constant; and 3. The average velocity at the barrier top increases with V_{DS} and then saturates at a limit, which is the average velocity of a thermal equilibrium hemi-Fermi-Dirac distribution, and the magnitude of saturated velocity increases with gate voltage.



(a)

(b)

Fig 1. Cross section sketches for (a) a bulk silicon MOSFET, and (b) a double gate MOSFET.

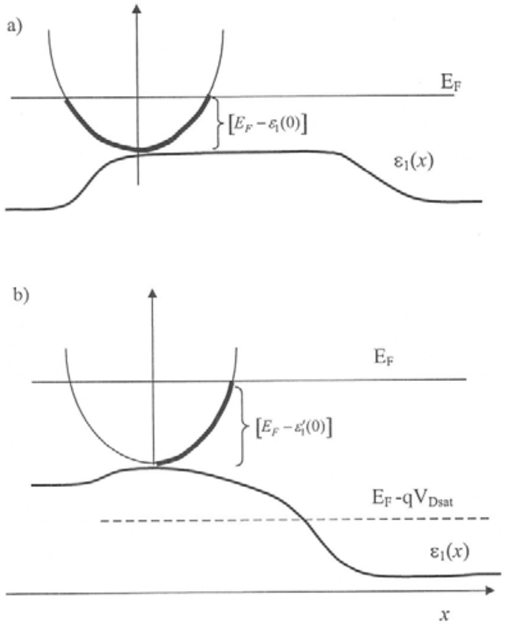


Fig 2. Conduction band from source to drain with the E-k diagram shown at the top of the barrier from source to drain at (a) equilibrium and (b) high drain bias

At equilibrium, as Fig 2 shows, two fluxes of electrons exist in the channel. One goes in the positive direction and the other goes the opposite way. In the E-k diagram (a), same amount of electrons travel in the channel with different k. The net flux from source to drain is zero. However, at high drain bias, all the electrons shown in Fig 2 (b) flow in the positive direction. But the amount of electron keeps the same in both cases. At the barrier top, by summing all the electrons over their momentum considered, the net current from source to drain can be achieved. In the model, if a transmission coefficient T is defined for the probability of electrons to arrive at drain from the source, then T=1 in the ideal ballistic model.

In the case where scattering is present, the transmission coefficient can be defined by the mean free path of electrons λ_0. At low drain bias, $T = \frac{\lambda_0}{\lambda_0 + L}$, where L is the channel length. By applying Einstein relation, λ_0 can be related with the effective mobility as $\frac{\lambda_0 v_t}{2} = \frac{k_B T_L}{q}\mu_{eff}$, where v_t is the electron velocity at thermal equilibrium $v_t = \sqrt{\frac{2k_B T_L}{\pi m*}}$, k_B is the Boltzmann constant, T_L is the lattice temperature, q is the electron charge, and μ_{eff} is the effective mobility in the channel. Then the current in the channel can be written as

$$I_D = \left(\frac{W}{L + \lambda_o}\right)\mu_{eff}\, C_{ox}\left(V_G - V_T\right)\, V_D$$

, where W is the channel width, Cox is the oxide capacitance, V_G, V_T and V_D are the gate voltage, the threshold voltage and the drain voltage separately.

At high drain bias, the transmission coefficient is defined as $T = \frac{\lambda_0}{\lambda_0 + l}$, where l is much less than the channel length L. Normally we assume in the channel, all the scattering is elastic. There is no energy loss for electrons. As shown in Fig 3, unless the electrons in the absorbing region get thermal energy high enough, they cannot be scattered back to the source end. l is defined as the distance over which the first $K_B T_L/q$ of potential drops from the barrier top. Once electrons go beyond l, they will be unlikely to return to the source after scattering.

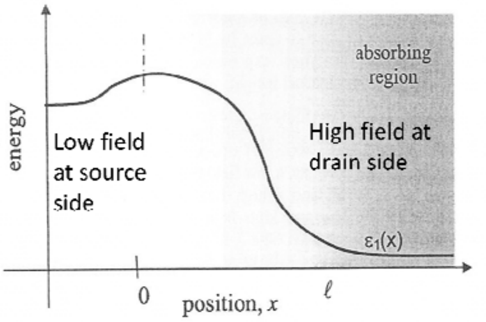


Fig 3. The conduction band plot for MOSFET under high drain bias

We can define a parameter B to compare the maximum current within or outside the ballistic regime:

$$B = \frac{I_D(\text{on})}{I_D(\text{on} - \text{ballistic})} = \frac{T}{2 - T} = \frac{\lambda_o}{2\ell + \lambda_o}$$

It is worth pointing out that so long as $\lambda_o >> 2\ell$, we have B close to 1. This means in order to get the current close to the ballistic limit, we really don't have to be in the ballistic regime. So long as the drain bias is very high, l can be much smaller than the mean free path of electrons. Under this condition, a current value closed to the ballistic limit can be achieved.

We may notice that the above model developed for silicon MOSFET does not consider inelastic scatterings like optical phonon scattering, which is essential in nitride based HEMTs. We are going to incorporate the polar optical phonon scattering into the parameter l. And more general assumptions are needed to deal with inelastic scatterings in nitride devices. This will be our main work for this project.