Non-tunneling origin of the 1/f noise in SiC MOSFET

Kin P Cheung and Jason P Campbell
National Institute of Standards & technology, Gaithersburg, MD, USA

Abstract: **It has long been established that MOSFET random telegraph noise and the cumulative 1/f noise is the result of inversion charge tunneling in and out of bulk traps in the gate oxide near the interface. The tunneling nature is a key concept upon which the technique of trap profiling using 1/f noise is based on. In this work, we examine the tunneling pathways in SiC MOSFETs and show that the 1/f noise observed in SiC MOSFETs is likely of a completely different nature involving above band edge interface states that do not require tunneling to capture the inversion charge.**

While the origin of 1/f noise remains a challenging subject, a consensus had been reached for the case of silicon MOSFETs [1-5]. It is generally accepted that random telegraph noise (RTN) and its cumulative effect, 1/f noise, in silicon MOSFETs is due to capture and emission of charges in trap states in the gate dielectric. It is universally stated that the capture and emission of charges by these states are by a tunneling mechanism which can only happen to bulk traps near the interface. Indeed, this tunneling nature is the foundation of the technique of using 1/f noise for trap profiling [6, 7]. In this work, we examine the available tunneling pathways to show that the RTN and 1/f noise in SiC MOSFETs is not due to bulk traps and does not have a tunneling origin.

MOSFET RTN is generally accepted as the result of charge capture/emission by single bulk traps and 1/f noise is the superposition of RTN events from many traps with different time constants (capture and emission) [8-11]. To explain the time constants as well as the observed thermal activation of RTN, it was concluded that the tunneling process must be inelastic in nature and that a lattice relaxation must be involved in the charge capture process. Working backwards from the measured time constants, the estimated lattice relaxation was between 20 meV to 150 meV [12, 13]. This small relaxation energy upon the capture of a charge is remarkable in that it is not consistent with the flexible network nature of amorphous SiO_2 [14]. Furthermore, direct measurements of SiO_2 defect relaxation energy found a value of 1.5 eV [15, 16]. Since the small relaxation energy was obtained by working backwards from measured time constant, this discrepancy clearly points to basic conflict in the most important parameter in the conventional RTN model. In fact, if one accepts the 1.5 eV relaxation energy, RTN cannot be explained by the existing model.

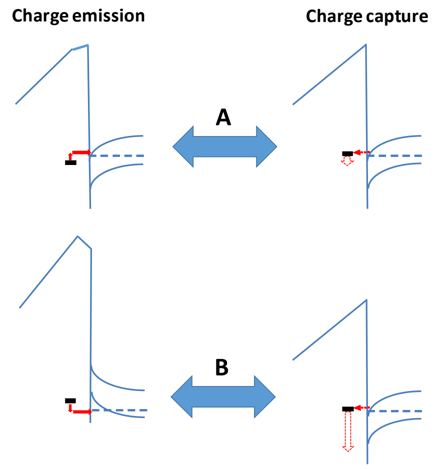

Fig. 1 RTN models showing charge capture and emission through tunneling. A represents the conventional model involving the "sheet charge approximation" and B represents the new model involving the local field of individual trapped charge.

In a recent paper [14], it was shown that the smaller relaxation energy of the existing model originates from the use of the universally accepted "sheet charge approximation" in treating the problem of trapped charge. Instead of this approximation, the recent work aims to capture the localized nature of each trapped charge and its associated electric field [14]. This approach has led to a new understanding of RTN that is compatible with the 1.5 eV relaxation. Fig. 1 illustrates the conventional and the new [14] RTN model of charge capture/emission.

Notice that fig. 1B indicates that the local field of a trapped charge changed the band bending from inversion to strong accumulation after a charge is captured. Notice also the large difference in energy relaxation in the charge capture process between the two models as indicated by the broken red arrow pointing downward. This is the most important difference. as in the conventional model, emission proceeds back to the conduction band where charge capture originated. In the new local field model, emission proceeds to the valence band instead. We emphasize that the local field as well as the strong

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relaxation are physical realities that have been unheeded in the conventional model, not approximations introduced to simplify the treatment. On the other hand, the "sheet charge approximation" was introduced to simplify the treatment and the small relaxation energy was a fitting parameter under this approximation. Thus, we argue that the new model is a big step towards a more complete picture of charger capture/emission.

Notice that the 1.5 eV relaxation is larger than the silicon band gap. This has important implications to silicon devices and conveniently locates the electron-captured relaxed trap at an energy favorable to for reemission to the valence band. Although the emission is no longer to the conduction band, the tunneling nature of the RTN is preserved. When dealing with wide band gap semiconductor devices such as SiC MOSFETs, this capture/emission pathway is no longer possible. Yet, it was reported that SiC MOSFETs have 1/f noise behavior very similar to those of Si MOSFETs [17]. This problem is illustrated in fig. 2 for SiC/SiO_2 MOSFETs.

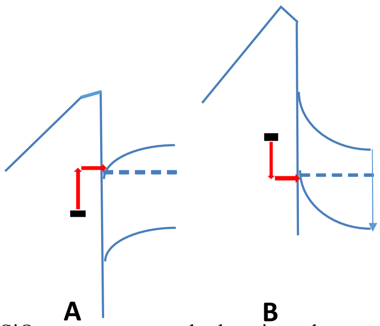

Fig. 2 SiC/SiO_2 post capture and relaxation, electron emission pathway for A, the conventional model involving "sheet charge approximation" and B, new model involving local field.

Since the 1.5 eV relaxation is an experimentally measured value [15,16] that is consistent with the physics of a flexible SiO_2 network [14], it must be accounted for in both the conventional model and the new model. Fig. 2A shows, for the conventional model, that the emission process must provide at least 1.5 eV of activation energy to occur. The probability to do so is extremely low and therefore would not regularly occur. For the new model shown in fig. 2B, the situation is also problematic. Since the bandgap of SiC is greater than 3 eV, it is easier to reemit to the conduction band rather than to the valence band as shown. When emitting to the conduction band, the activation energy is still 1.5 eV and unfavorable. Thus, we have a situation that both the new and the conventional model fail to explain the RTN and therefore the 1/f noise phenomenon in wide bandgap SiC/SiO_2 MOSFETs.

In [14], it was further discussed that energy relaxation is roughly half if the trapped charge is precisely at the interface. Physically, this is because only half of the media surrounding the charge is polar and flexible, the other half is non-polar and rigid. As the trap location moves further into the bulk of the oxide, the relaxation energy rapidly transitions to the full relaxation value (1.5 eV) within a fraction of a nanometer. Fig. 3 illustrates the energetics of emission for true interface states, very near interface states, and bulk states.

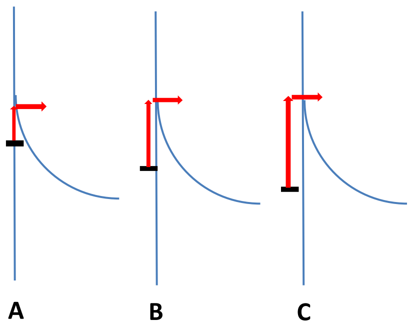

Fig. 3 Emission pathway of trapped electron for three trap locations: A, precisely at the interface; B, very near the interface; and C, near interface.

As shown in Fig. 3A, when the trap is right at the interface, only half of the SiO_2 media can rearrange screen the trapped charge and energy relaxation is essentially cut in half (0.75 eV). When the trapped charge is deeper into the bulk of the oxide, the energy relaxation is 1.5 eV (fig. 3C). In between these two extremes, the relaxation energy varies [14] (fig. 3B). Fig. 3 also depicts a very strong band bending, which is a characteristic of wide band gap semiconductors biased in strong accumulation as would be true in the local field picture [14]. As shown, the activation energy for emission is slightly lower than the relaxation energy for the true interface states near the top of the band, the barrier becomes very thin and tunneling can be more efficient than absorbing more phonons.

For traps located deeper into the oxide, the relaxation energy increases rapidly and the activation energy must reach closer to the top of the conduction barrier because there is an additional, much higher barrier layer due to the oxide. This is the reason activation energy in fig. 3B rises so dramatically. As the trap gets very deep into the bulk, (fig. 3C), the activation energy equals the relaxation energy. Thus, as soon as the trap is just off the interface, the activation energy makes emission very unlikely. We therefore conclude that only the interface states have the potential to explain the RTN and therefore RTN and 1/f noise. Tunneling is not involved, at least for the capturing process.

As pointed out by McWhorter [8], another condition for 1/f noise is that the capture and emission must involve many traps with a broad range of time constants. The emission time of an electron in a relaxed interface state is:

$$\tau = \frac{1}{\nu e^{(-\Delta E/kT)}} \qquad (1)$$

where v is the lattice vibration frequency taken as 10^{13}/s; ΔE is the activation energy; k is Boltzmann's constant; T is temperature. Fig. 4 shows the emission time and activation energy relationship.

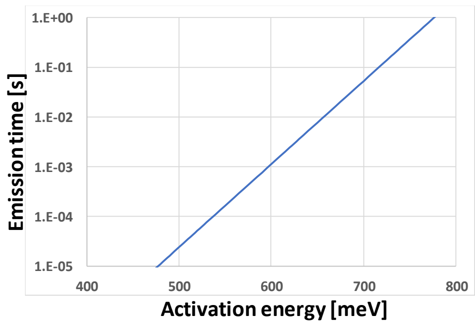

Fig. 4 Emission time as a function of activation energy.

For experimentally observable noise, the time constant ranges from tens of microseconds to seconds. In other words, the activation energy must be between 500 meV and 800 meV. Such a range is possible if there is a high density of interface traps at energy around the conduction band edge. Fig. 5 shows how a range of near-band edge trap energy produces a range of activation energies.

For observable RTN and 1/f noise, the capture time must also be in a similar range. Notice that in fig. 5 some of the traps are above the Fermi level, requiring thermal activation to reach. That will reduce the capture probability, or equivalently increase capture time. In addition, when an electron is captured from the inversion layer into one of the interface trap states, it can either reemit right back out or be trapped, meaning relaxation occurs before reemission. At energies above the Fermi level, reemission dominates because relaxation involves an energy barrier corresponding to the configurational difference between the initial empty state without an electron and the final stable state with a captured electron [14]. This means that states above the Fermi level have longer capture time. The combined thermal activation energy to reach these states and the activation energy to reach the new configuration quickly limit the range of energies above the Fermi level that can be involved. The boundary can be obtained by realizing that the emission size limited the top end of energy barrier to be 500 meV below the conduction band edge. Assuming 750 meV of energy relaxation, the maximum trap energy before capture is 250 meV above the band edge. Due to quantum confinement, the Fermi level is somewhere within the first sub-band which is 100 meV to more than 200 meV above the conduction band edge. We therefore only need to thermally access a few tens of meV, or a couple of kTs.

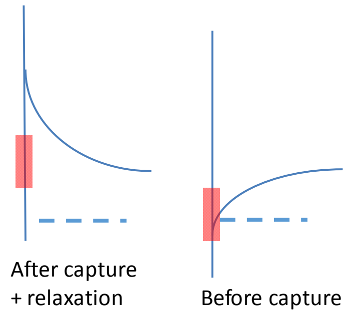

Fig. 5 High density of interface traps at energy around the conduction band edge can produce a range of activation energy after electron capture and relaxation.

For interface states with energy below the Fermi level, capture becomes more efficient because reemission requires energy. The competition between capture (with relaxation) and reemission increasingly favors capture. At some energy below the Fermi energy, capture becomes too efficient and the trap will always be filled. At this point noise cannot be observed. While we do not know the size of the energy barrier involved in configuration change, we can get a lower bound of the interface state energy from the emission consideration. With the maximum activation energy for emission at 800 meV and the relaxation energy at

750 meV, we know that the lowest energy interface states that contributes to RTN and 1/f noise is at most 50 meV below the conduction band edge.

High quality silicon MOSFETs do not have high densities of interface states near the band edge [18] so the tunneling nature of noise is seemingly correct. For SiC MOSFETs, it is well known that high density of interfaces states exists at the band edge [18, 19]. Since we already discussed that the tunneling picture does not fit wide bandgap MOSFETs, this band edge interface states based, non-tunneling mechanism has solid foundation. We note that 1/f noise in SiC MOSFETs has been explained previously using interface states [21], but the model employed was for the tunneling process and therefore problematic.

We note that the exact values of relaxation are somewhat approximate as the defect identity does play some role in the overall relaxation energy. In the case of SiC MOSFETs, where substantial doses of nitrogen are incorporated at the interface and near interface oxide regions, the relaxation energies may differ slightly than those reported here for the pure SiO_2 network. The addition of nitrogen into the SiO_2 glass network will 'stiffen' the resultant insulator network and reduce the relaxation energies somewhat. However, even high-density nitrogen incorporation would leave the average SiO_2 network (average bond energies) essentially unchanged. Consequently, we take the pure-SiO_2 relaxation energies discussed above as very good approximations.

Summary: As a flexible network of highly polar bonds, SiO_2 produces a large lattice relaxation energy of 1.5 eV. When this physical reality is accounted for, RTN and therefore 1/f noise cannot be explained in the conventional model where the "sheet charge approximation" is used to treat trapped charges. Abandoning this approximation and recognizing the localized nature of the trapped charge and its associated electric field, RTN of silicon MOSFETs can be explained without abandoning the 1.5 eV relaxation energy. However, when wide band gap semiconductors such as SiC MOSFETs are involved, the tunneling based models, conventional or local field, involving bulk traps do not work. Acknowledging that there are high densities of interface states at the band edge in SiC MOSFETs, a new, non-tunneling based model involving true interface states is developed that can successfully explain the observed RTN and consequent 1/f noise in SiC MOSFETs.

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