

EXPLANATION FOR REDUCED FOWLER-NORDHEIM TUNNELING CURRENT IN ULTRATHIN SILICON NITRIDE GATE DIELECTRIC

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ABSTRACT

It is reported that Fowler-Nordheim (FN) current is effectively reduced due to the use of silicon nitride instead of silicon dioxide as gate dielectric. In this paper we made a comparative study of FN tunneling current in both silicon dioxide and silicon nitride and explain the reason behind lower FN tunneling current in silicon nitride, introducing the concept of quantum tunneling transmission coefficient and charge trapping probability.

It is concluded that, provided the dominant current conduction mechanism is electron tunneling, the si-oxy-nitride film of dielectric is generally less leaky than its counterpart si-oxide of the same equivalent oxide thickness (EOT). This comes about due to the nitride's larger physical thickness for a given EOT, despite the fact that it has a lower barrier height [5]. In this paper we intend to explain the reduction phenomenon.

1. INTRODUCTION

Unintentional leakage currents through gate dielectrics is a major reliability issue in high speed MOSFETs, capacitors used in DRAMs and NVMs (nonvolatile memories). As gate oxides become thinner, the conductance of oxide layers increases. For relatively thicker oxides FN current contributes the major leakage component. The main cause of 'write disturb' and 'erase disturb' in NVMs to be Fowler-Nordheim current at high electric fields[1]. The performance degradation of the conventional devices happens mostly due to tunneling leakage current. The tunneling leakage current can be modeled by the numerical integration using Airy technique[2], semi-empirical WKB approximation [3] and other quantum-mechanical calculation [4]. The dependency of tunneling current (both Fowler-Nordheim (FN) Tunneling and Direct Tunneling (DT)) on the oxy-nitride film or the nitrogen content in gate insulation has recently been observed [5]. It has been reported (figure 1) that the DT current reduces greatly with the increasing nitrogen content in the gate insulator while the FN tunneling current has a minimum value at some intermediate mixture of nitrogen and oxygen i.e., silicon-oxy-nitride film.

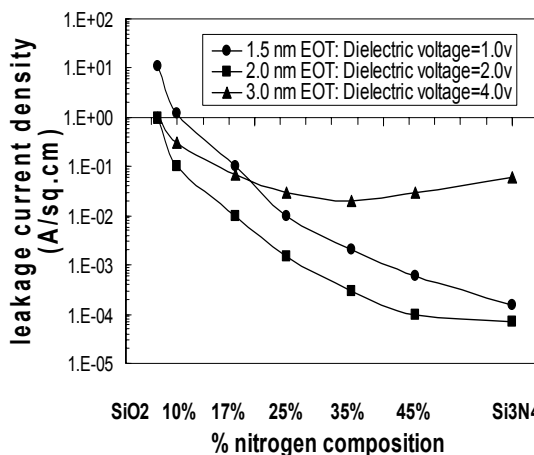


Fig. 1: Relationship between tunneling current and dielectric film composition: dependence on oxygen/nitrogen concentration[5].

2. THEORY

The equation relating capacitance and thickness is as follows

$$C = \frac{\epsilon A}{D} \quad \text{-----(1)}$$

Here, C is capacitance, ϵ is dielectric constant and D is insulator thickness.

The capacitance due to the oxide and nitride are to be same for similar effect.

So,

$$C_{ox} = \frac{\epsilon_{ox} A_{ox}}{D_{ox}} = C_{ni} = \frac{\epsilon_{ni} A_{ni}}{D_{ni}} \quad (2)$$

Where the subscripts ox and ni stand for si-oxide and si-nitride related parameters respectively. For same capacitance of same area the relation between thicknesses is

$$D_{ni} = \frac{\epsilon_{ni}}{\epsilon_{ox}} D_{ox} \quad (3)$$

The typical value of dielectric constants are $\epsilon_{ox} = 3.9$ and $\epsilon_{ni} = 6.0$ [5].

So, we get

$$D_{ni} = 1.54 D_{ox} \quad (4)$$

Now to compare the tunneling probability of si-nitride and si-dioxide, we can use the following equation of the transmission coefficient [6],

$$T = \frac{16 E (V - E)}{V^2} \exp(-2\alpha D) \quad (5)$$

Where

$$\alpha = [2 m_e (V - E) / \hbar^2]^{1/2}$$

is the rate of decay of wave function inside the barrier, E is electron energy, V is barrier height, D is barrier width, m_e is mass of electron = 9.1×10^{-31} kg and \hbar is Planck's constant / $2\pi = 1.05 \times 10^{-34}$ Js.

3. RESULTS AND DISCUSSION

Figure 2 compares between the transmission coefficients of two dielectrics namely si-dioxide and si-nitride.

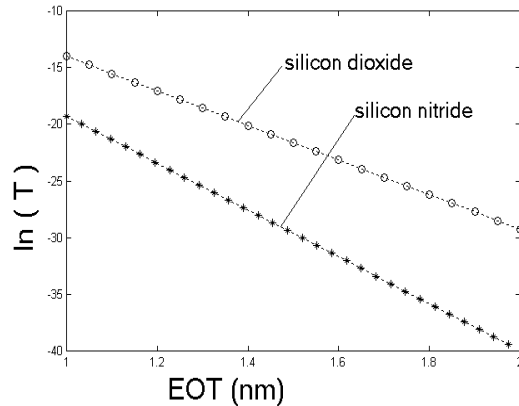


Fig.2: Transmission coefficient vs. equivalent thickness.

It is evident from the figure that the transmission coefficient is smaller for silicon nitride than that of silicon oxide for all EOT values.

Now, the tunneling current can be obtained from the product of the carrier charge(q), carrier velocity(V_R) and carrier density(n). Here the velocity equals the Richardson velocity(V_R), the average velocity with which the carriers approach the barrier while the carrier density equals the density of available electrons multiplied with the tunneling probability(T), yielding:

$$J_{FN} = q n V_R T \quad (6)$$

Figure 2 clearly shows that for all EOTs in the figure the transmission coefficient for silicon nitride is less than transmission coefficient for silicon oxide. Using equation (6) it can be easily stated that the FN tunneling current will be less for silicon nitride than that of silicon oxide. Figure 3 demonstrates the fact which is a plot of $\ln(J)$ vs $\ln(T)$ with an electric field of 6 MV/cm.

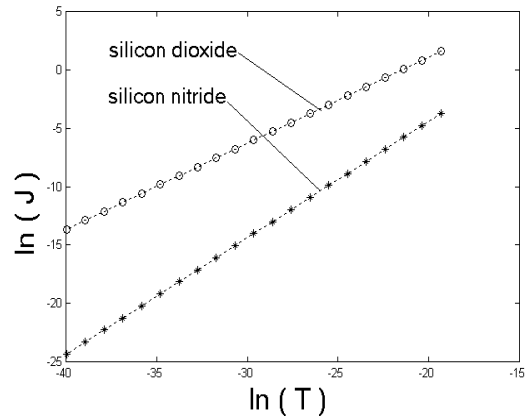


Fig. 3: Comparing $\ln(J)$ vs $\ln(T)$ characteristics of silicon dioxide and silicon nitride.

When potential is applied across the gate insulator, theoretically a potential gradient of constant slope is observed. The potential decays from the polysilicon cathode to the silicon substrate. There exist a finite barrier height at the metal (polysilicon)-insulator interface. Classically electrons of lower energy cannot pass through the barrier. But in this small dimensional region quantum mechanical effect enables the electrons to tunnel through the barrier. Electrons can tunnel either directly from the conduction band of the metal to the conduction band of the silicon substrate or they can first emerge in the insulator conduction band and then hop to the silicon substrate. The first process is known as direct tunneling(DT) which takes place if the barrier is thin and it consists of crossing a trapezoidal energy

barrier. The second process is known as Fowler-Nordheim (FN) tunneling which requires to cross a triangular barrier and takes place when the barrier thickness is relatively large. These two tunneling phenomenon are schematically shown in figure 4 in the next page.

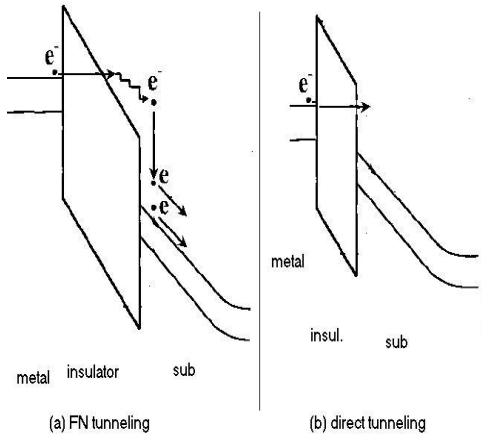


Fig. 4. Two types of tunneling phenomenon.

FN tunneling current is proportional to the applied electric field. The equation of the tunneling current is given by

$$J_{FN} = A E_{ins}^2 \exp(-B / E_{ins}) \quad \text{-----(7)}$$

Where

E_{ins} is electric field in the gate insulator,

$$A = 1.54e-6 (m_e / m_{ins})(\Phi_{mi})^{-1}$$

$$B = 6.823e7 (m_{ins} / m_e) (\Phi_{mi})^{3/2},$$

m_e is free electron mass, m_{ins} is effective mass of electron in insulator and Φ_{mi} is potential barrier at metal-insulator interface.

It is clear from the above equation (7) that the increase in electric field will increase FN tunneling since the square of electric field outside is playing more dominating role than the inverted electric field in the exponential power.

When electrons gain sufficient energy from the electric field to become 'hot electron' and emerge into the gate insulator, they may cause impact ionization within the insulator and create electron-hole pair (EHP). The so created electron and hole are accelerated by the electric field and electron moves toward the substrate(anode) and hole moves towards the metal (cathode). However the carrier mobility is quite low inside the insulator and are easily trapped in the crystal defect sites and different other trap centers. The holes are trapped near the metal-insulator interface, inside the insulator and similarly electrons are trapped near the substrate.

These trapped charges assist the existing electric field and increase the slope of the electric field. Clearly, due to equation (6) the FN current will also increase. Thus trapped charges play role to increase the FN tunneling current. Figure 5 shows the fact schematically.

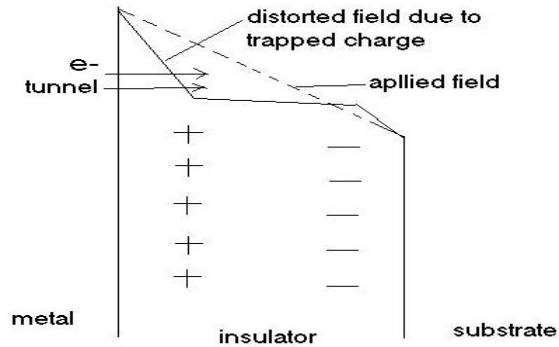


Fig. 5. Trapped charges assisting FN tunneling

At this point we can turn to the comparison of charge trapping between silicon oxide and silicon nitride.

Reported research results identified intrinsic defects (in the form of three-fold coordinated Si centers and oxygen vacancies), as well as extrinsic defects (hydrogenic species, phosphorus, and boron atoms), as charge trapping centers in the Si-SiO₂ systems. Evidence gained from the study deciphered the atomic structures of two recently detected trapping centers, known as the E and X (also called S) centers, in bulk SiO₂ and in the near Si-SiO₂ interfacial region of MOS systems.[7][8][9] Additionally, a new defect, called the Y center, was identified in the near-interfacial region of the MOS system. Three-fold coordinated Si centers with mixed Si-O coordination were proposed as the precursors to the near-interface (border) traps. These centers were first observed in 250 keV helium-ion-implanted amorphous SiO_x (1<x<2) films [10]. Besides it was shown that the nice interface properties of the SiN/Si system were preserved in the TiO/SiN/Si system, suggesting that the ultra-thin SiN layer is indeed a good interfacial buffer. Transistors made with TiO/SiN as the gate dielectric demonstrate excellent electrical quality. Reliability test results of the TiO/SiN stack indicate low trapping probability, high breakdown strength, and very little SILC (Stress induced leakage current)[11]. Moreover, it is demonstrated that both hole trapping and electron trapping are suppressed by the incorporation of nitrogen into the gate oxide [12].

The above experimental determinations can be summed up to conclude that silicon nitride has lesser charge trapping probability than its counterpart silicon oxide. Silicon nitride has better interfacial property than that of silicon dioxide. So charge trapping in the silicon nitride interface with semiconductor is less. Moreover an implantation of nitrogen in the oxide also lessen charge trapping. If more charges are accumulated, the field will be distorted more and FN tunneling will be more prominent which happens the case for silicon oxide. Since in nitrogen implanted gate insulation the charge trapping is less the field is less distorted and hence the FN tunneling current is also less. Figure 6 demonstrates the fact.

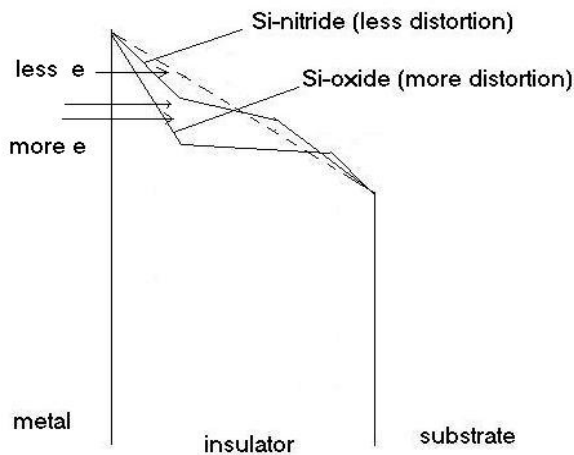


Fig.6 : Comparison of distortion between two insulators: silicon nitride and silicon oxide.

From the discussion it can be summarized that the FN tunneling current through the silicon nitride gate insulator is reduced due to both smaller transmission coefficient and less charge trapping probability in silicon nitride gate dielectric than pure silicon dioxide dielectric.

4. CONCLUSION

We carried out a comparative study of FN tunneling current through silicon dioxide and silicon nitride gate dielectrics and explained the reason behind reduced FN tunneling current in the silicon nitride gate dielectric introducing the concept of quantum tunneling transmission coefficient and charge trapping probability. Proper understanding of the phenomenon will be of great help to understand device phenomenon and to model these phenomenon

with enhanced accuracy. The attractive feature of reduced FN tunneling current through silicon nitride will certainly make it a potential candidate for ultrathin gate dielectrics in advanced ULSI technology.

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