Fowler–Nordheim hole tunneling in \( p\)-SiC/SiO\(_2\) structures

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We report the confirmed occurrence of Fowler–Nordheim hole tunneling in \( p\)-4H–SiC metal-oxide-semiconductor capacitor structures. The effective mass for holes in the oxide is found to be in the range of 0.35\( m \)–0.52\( m \), where \( m \) is the free electron mass. © 2000 American Institute of Physics. [S0003-6951(00)00342-9]

A fundamental process in the description of the current-voltage \((I-V)\) characteristic of a metal-dielectric-semiconductor structure is the advent of Fowler–Nordheim (FN) tunneling.\(^1\) At large fields, the carriers may tunnel through the forbidden region of the insulator into the allowed states of the insulator. This process has been observed and widely studied in Si-based metal-oxide-semiconductor (MOS) structures.\(^2\) The process is intimately related to the reliability of the oxide, as carriers may cause defect formation in the oxide or at the anode/oxide interface which finally results in oxide breakdown. Similar to the FN tunneling of electrons from the cathode to the oxide conduction band, FN tunneling of holes from the anode to the oxide valence band may also occur. In Si-based MOS structures, this is not possible due to the small band gap of Si (1.12 eV), which leaves a large hole barrier of 4.65 eV. Instead, hot-hole injection from the anode has been shown to occur in Si, where the energy to create hot holes at the Si anode is derived from high-energy electrons that tunnel from the cathode into the oxide conduction band.\(^3\)–\(^5\) However, in SiC-based MOS structures, FN tunneling of holes is possible due to the wide band gap of SiC polytypes and a large band offset of 6 eV from the top of the valence band to the oxide conduction band.\(^6\) In this letter, we report clear observation of FN tunneling of holes in \( p\)-4H–SiC-based MOS structures.

FN tunneling of electrons is expressed as\(^2\),\(^7\)

\[
\frac{J}{E^2} = A \exp(-B/E),
\]

where \( J \) is the current density in \( \text{A/cm}^2 \), \( E \) is the oxide field in \( \text{V/cm} \), and the pre-exponent \( A \) and slope \( B \) are given by

\[
A = \frac{e^3 m}{16\pi^2\hbar m_{\text{ox}}\phi_0} = 1.54 \times 10^{-6} \frac{m}{m_{\text{ox}}\phi_0} \quad (\text{A/V}^2),
\]

\[
B = \frac{4}{3} \frac{(2m_{\text{ox}})^{1/2}}{e\hbar} \frac{\phi_0^{3/2}}{m}.
\]

where \( e \) is the electronic charge, \( m \) is the free electron mass, \( m_{\text{ox}} \) is the electron mass in the oxide, \( 2\pi\hbar \) is Planck’s constant and \( \phi_0 \) is the barrier height expressed in electron volts. A plot of \( \ln(J/E^2) \) vs. \( 1/E \) called a FN plot gives the value of the slope constant \( B \), from which the \( (m_{\text{ox}}/m)^{1/2}\phi_0^{3/2} \) product can be obtained. Then, with a known effective mass, \( \phi_0 \) can be calculated, or with a known \( \phi_0 \), the effective mass can be calculated. Utilizing the above tunneling equation in the Si-based MOS systems, the effective mass for the electrons in the oxide has been calculated to be in the range of 0.42\( m \) (Ref. 2) to 0.5\( m \).\(^7\) The same equation is applied to FN tunneling of holes in \( p\)-4H–SiC-based MOS structures and the effective mass of holes in the oxide is calculated.

The samples utilized in the present study involve SiO\(_2\) grown on \( n\)- and \( p\)-type 4H–SiC, and annealed in NO at 1150°C for 2 h as described in our earlier study.\(^8\) Room temperature current-voltage \((I-V)\) measurements with MOS capacitor test structures in accumulation reveal the occurrence of FN tunneling of electrons from \( n\)-SiC cathode into the oxide conduction band and FN tunneling of holes from \( p\)-SiC anode into the oxide valence band.

Figure 1 presents the band diagrams for Mo-gated \( n\)- and \( p\)-type 4H–SiC MOS capacitors in accumulation with a large field across the oxide. It can be observed that at high fields, FN tunneling of electrons into the oxide conduction band takes place in \( n\)-4H–SiC MOS structures, which has also been demonstrated by other research groups.\(^9,10\) However, in \( p\)-4H–SiC MOS structures, FN tunneling of holes into the oxide valence band occurs. The observed FN tunneling of holes from the SiC anode in \( p\)-4H–SiC MOS is due to the small hole barrier of 2.9 eV as compared to the large electron barrier of 3.8 eV when utilizing Mo as gate (cathode) material. As described above, a possible competing mechanism for current generation at this bias is electron tunneling from...
the cathode to the semiconductor conduction band. This is the case in Si, preventing the direct observation of hole tunneling. However in SiC, the hole barrier of 2.9 eV is substantially smaller than the electron barrier and hole tunneling dominates. This hole barrier at the p-SiC anode will be less than the electron barrier when utilizing gate (cathode) metals like Al, Ni, Cu, Au, Ag, Pd, Ti, Ta, Mo, Cr, and many others, which have large work functions.\textsuperscript{11}

Figure 2 presents typical $I-V$ plots for MOS capacitors in accumulation showing increased current through the oxide due to the onset of FN tunneling of electrons in $n$-4H–SiC MOS with a Mo gate and the FN tunneling of holes in $p$-4H–SiC MOS with Mo and Au gates. The $I-V$ curves for the $p$-4H–SiC with Mo and Au gates are nearly identical indicating that the increased current at high oxide fields is mainly due to the hole injection from the 4H–SiC anode. The currents would only be identical if the dominating barrier heights are the same, i.e., the hole barrier height of 2.9 eV. Electron tunneling from Au and Mo would result in substantially different currents due to their different work functions of 5.1 and 4.7 eV, respectively.

Figure 3 shows FN plots for the three MOS capacitors at high oxide fields shown in Fig. 2. The slope of the FN plot on $n$-4H–SiC MOS having Mo gate is $206 \text{ MV/cm}$. Using this slope, and an electron effective mass in the oxide of 0.42 $m_e$\textsuperscript{10} gives the electron barrier height from $n$-SiC conduction band to the oxide conduction band of 2.78 eV. Adding the 4H–SiC band gap of 3.26 eV to the above value confirms the band offset determined by Afanas’ev et al.\textsuperscript{6} to be about 6 eV from the oxide conduction band to the top of the valence band in SiC. The slope of the FN plots on $p$-4H–SiC MOS having Au and Mo gate metals is the same and is $\sim 200 \text{ MV/cm}$. This proves that FN tunneling of holes from the p-SiC anode to the oxide valence band is occurring, as the holes see a fixed barrier of 2.9 eV at the surface. There has been one other report of hole injection in $p$-6H–SiC MOS capacitor,\textsuperscript{12} but to the authors’ knowledge, this is the first confirmation of the FN-hole tunneling phenomena, performed by utilizing two electrodes of Au and Mo having different work functions. Using this hole barrier height of 2.9 eV at the surface of the $p$-4H–SiC, the effective mass for holes in the oxide is evaluated to be about 0.35 $m_e$.

We want to stress, however, that this value does not necessarily reflect the effective mass of holes in the oxide alone if tunneling is the only process occurring. The holes tunnel from the SiC substrate into the metal gate. In both materials, holes have a different intrinsic effective mass than in the oxide and effective mass differences along the transport direction can produce scattering even in the absence of potential barriers for the carriers.\textsuperscript{13} However, incoherent processes take place in the oxide and holes release energy to the lattice. This is demonstrated by the defect formation in the oxide that results in breakdown. We can thus argue that holes drift mostly in the oxide and assign the effective mass to the oxide alone. We also point out that band bending at the SiC/SiO$_2$ can allow holes to tunnel across the oxide at lower energy values than at flat band conditions,\textsuperscript{14} thus reducing the effective barrier for tunneling. Finally, the experimental error on the determination of the band offset from the SiC valence band to the oxide conduction band by internal photoemission\textsuperscript{6} is about 0.2 eV and this can further reduce the barrier for tunneling. Taking into account all the above effects we estimate an effective mass for holes in the oxide ranging from 0.35$m_e$ to 0.52$m_e$.
In conclusion, FN tunneling of holes in $p$-SiC is shown to occur and the effective mass for holes in the oxide is calculated from the slope of the FN plot to be in the range of $0.35m$ to $0.52m$, where $m$ is the free electron mass. The detailed understanding of this mechanism provides new insights into the reliability/breakdown issue in SiC-based MOS structures and interesting information as to the different behavior of Si and SiC based systems.

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