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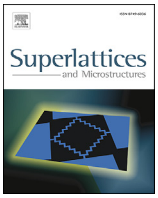

Voltage and oxide thickness dependent tunneling current density and tunnel resistivity model: Application to high-*k* material HfO_2 based MOS devices

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ABSTRACT

In this paper presents a straightforward efficient investigation of tunneling current density for ultra thin oxide layer based metal-oxide-semiconductor (MOS) devices to realization the gate current as a function of applied potential and oxide thickness. Solutions to the Schrödinger's wave equation are evolved for the different potential energy regions of the MOS device considering appropriate effective mass for each region. For finding approximate mathematical solutions to linear differential equations using spatially changeable coefficients the Wentzel-Kramers-Brillouin (WKB) approximation technique is considered. A p-substrate based n-channel MOS device has been analyzed consisting of SiO_2 material as the oxide dielectric along with high-*k* material HfO_2. The tunnel resistivity is correspondingly assessed employing this tunneling current density model. Synopsys Technology Computer Aided Design (TCAD) tool results are employed to validate the analytical model. Tremendous agreements among the results are observed.

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1. Introduction

For last few decades scaling of the current silicon established complementary-metal-oxide-semiconductor (CMOS) technology for high speed and enhanced density has been the strength for the semiconductor manufacturing industry. But as the transistor physical dimension shrinks below a certain range, the performances of silicon based MOSFETs reduces owing to short-channel-effects (SCEs), hot-carrier-effects (HCEs) and tunneling current (leakage current). The reduction of the gate oxide thickness due to the scaling in the MOS devices of existing field-effect-transistors (FET's) significantly increases the prospect of gate tunneling current [1]. The possible phenomena which can contribute to unwanted leakage are tunneling through ultra thin oxide layer in the MOS structure. The idea of tunneling current plays an essential phenomenon in the modeling, simulation, design and improvement of nanoelectronic device technologies. The perceptions of the quantum electronics has come owing to the disappointment of classical mechanics in responding to the effects detected in nano dimensional MOS device technology. Because in the quantum mechanics, the particle using a very minute probability, tunnel through the oxide layer, therefore crossing the potential barrier. At this time the particle could use energy from its environments to tunnel through the potential barrier. There are numerous occurrences that have the similar activities as quantum

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Nomenclature

$U(x)$	Potential Energy at distance x
Φ_s	Work function of Semiconductor
V	Applied gate voltage
Φ_m	Work function of Metal
φ_{ox}	Energy band offset value
ψ_s	Surface Potential
E	Total energy in Metal
m_1	Effective mass of charge in metal region
m_2	Effective mass of charge in oxide region
m_3	Effective mass of charge in depletion region
m_4	Effective mass of charge in semiconductor region
ψ_m	Potential wave function in metal region
ψ_{ox}	Potential wave function in oxide region
ψ_{sd}	Potential wave function in depletion region
ψ_{sm}	Potential wave function in semiconductor region
V_{bias}	Bias voltage
w	Maximum depletion width
a	Oxide thickness
$\psi(x)$	Potential at distance x
$\hbar$	Planks constant
E_x	Electron energy
q	Charge on electron
$f(E)$	Fermi-Dirac function
m	Mass of an electron
Ai	Airy function of 1st kind
Bi	Airy function of 2nd kind
Ai'	Derivative of Ai
Bi'	Derivative of Bi
N_1	Number of electrons tunneling through the barrier from semiconductor to metal per unit area per second
N_2	Number of electrons tunneling through the barrier from semiconductor to metal per unit area per second
$T(E_x)$	Transmittance (probability of transmission)
J_T	Tunneling current density
σ	Tunnel resistivity

tunneling, therefore can be accurately defined by tunneling. Even though the scaling of CMOS technology employing SiO_2 as oxide material has got its limit, there is a prospect in thinning the electrical insulator thickness further with high-*k* dielectric materials and/or metal gates to achieve a greater physical thickness and thus reducing the direct tunneling current while retaining an effective low oxide thickness [2–4]. High dielectric constant insulating materials in the lanthanum group have shown better results as prospective replacement for SiO_2 [5 and 6]. If a high-*k* dielectric material substitutes SiO_2 material as a gate oxide for MOS structure, in addition to high-dielectric constant ($k > 3.9$), this material must have a reasonable energy gap and a barrier height relative to silicon greater than 1 V or at least greater than the supply voltage to be used within the dielectric. Among the applicants, metal oxide such as HfO_2 is quite promising having a suitable dielectric constant of about 22 [7–12] and a large band gap (~5.6 eV) [13]. Since it have superior dielectric properties, it exhibits low tunneling current, high enough conduction bands offset and good quality thermal stability on silicon substrates. Hence HfO_2 is most explored high-*k* dielectric material today.

Tunneling has been detected in MOS devices once the applied field is sufficient to sink single side of the potential barrier in the semiconductor-oxide interface, permitting tunneling into the conduction band of the insulator. The insulators having thicknesses approximately in the order of 70–1000 Å [8], remained thick sufficient to compete against direct tunneling into the conduction band of the other electrode. But, as soon as the insulators ensure thicknesses approximately a few nanometres (<5 nm), direct tunneling current at lesser fields cannot be unimportant. For these circumstances the potential barrier is not a triangular characteristic, nonetheless almost trapezoidal (not considering the barrier lowering owing to image force effects) [1].

On behalf of ultra thin oxide layer, the gate terminal tunneling current of MOS devices can turn into excessively enormous even at lesser gate potential owing to direct tunneling occurrence. The increased significance of gate tunneling current and

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