Current Applied Physics 14 (2014) 306–311

Contents lists available at ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

A wire-form emitter metal–insulator–semiconductor tunnel junction

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ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form
29 November 2013
Accepted 2 December 2013
Available online 14 December 2013

Keywords:
MIS structure
Cylindrical geometry
Band diagram
Tunneling current
Simulation

ABSTRACT

Physical effects arising due to change of configuration of a MIS system from planar to cylindrical, are theoretically analyzed. Attention is paid to the voltage partitioning and all the components of tunneling current. A simple simulation model is developed enabling prediction of the band diagram details and calculation of the currents. The trends expected with decreasing system radius are elucidated. Cylindrical geometry can be faced with when quantum wire is used as an electron emitter. Similar form may also be roughly attributed to an edge region of conventional MIS capacitors.

1. Introduction

The paper is devoted to the analysis of a behavior of a Metal–Insulator–Semiconductor (MIS) junction whose emitter has a cylinder shape. The metal wire is supposed to be surrounded by a concentric dielectric layer of thickness d and permittivity ε_I, and outside it there is an infinite semiconductor medium (Fig. 1). Such a system recalls the quantum-wire field effect transistor, but the emitter (gate) is placed not outside but inside the dielectric.

Leaving open a question on feasibility of this structure, one can claim that it may serve as a very simple model prototype for a half-quantitative analysis of non-planar geometry effects in MIS devices. Thinkable examples of the relevant cases are stripe- or edge-electrode effect [1] in thin-film capacitors. Undeniably, while the studies on planar MIS structures are numerous (e.g. Refs. [2–4]), not much effort has been so far undertaken toward understanding what occurs or might occur within other configurations [5,6]. This study was preceded by our work [7] where the spherical geometry has been focused upon. The cylindrical case constitutes another important geometry.

It is assumed (Fig. 1) that the outer insulator interface radius is R_0; the inner interface curvature is therefore $R_0 - d$. In a semiconductor, the band bending zone of width w is located between $r = R_0$ and $r = R_0 + w$ (in case of depletion–inversion, w is a depletion layer width). Near-surface quantization phenomena are considered only near the outer interface because much larger, than in a semiconductor, variety of states and bands in metal smears discretization and makes possible nearly any energy. Between the wire emitter and the bulk, a voltage V is applied. Concentration of mobile carriers in semiconductor near the outer interface is $N_s = N/2\pi R_0 L$ where N is a number of carriers in the structure segment of an arbitrary length L along the system axis. Regular planar coefficients (dielectric constants etc.) are taken for all materials – metal (Al), insulator (SiO_2), and semiconductor silicon (Si) [3,4].

Below we present the electrostatic model, including necessary formulas, explain the procedure of simulating currents and perform calculations for two different but equally practical situations of thermal equilibrium and of deep depletion in silicon. Reference to available experiment will be also made.

2. Model description

Like in planar geometry [3], the terminal bias V, and the quasi-Fermi levels shift $E_{FB} - E_{FW}$ (B = bulk, W = surface well) have to be specified for calculation. The dopant concentration N_{dop} (N_A or N_D) is also supposed to be known.

Anyway the field and potential distribution include the parts arising due to doping and due to carriers in the well:

$$F = F^{dop} + F^{well};\ \varphi = \varphi^{dop} + \varphi^{well}. \quad (1)$$

The doping-related part may be naturally renamed as depletion part for a reverse-bias condition. However for forward bias, it is a contribution of the charge in non-quantized states energetically

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1567-1739/$ – see front matter
http://dx.doi.org/10.1016/j.cap.2013.12.002

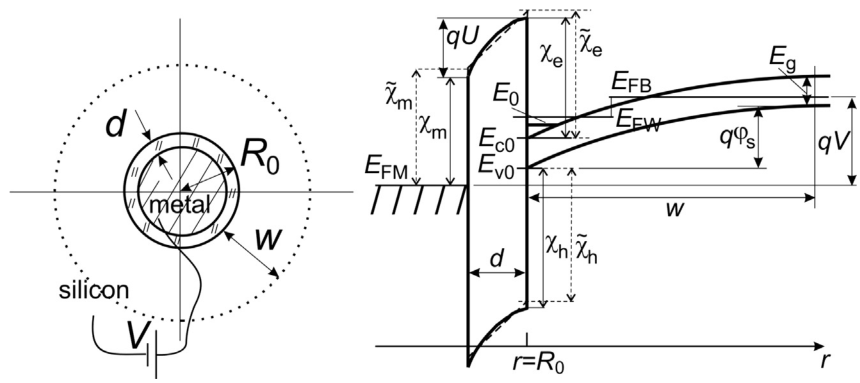

Fig. 1. Cylindrical MIS tunnel structure and corresponding band diagram (case depletion or inversion) with notation.

above the well. So the term “doping-related” is more universal than “depletion-layer-related”. The charge density in both cases is roughly qN_{dop}. Also it seems to be more correct to speak about the “well” contribution than to use the word “inversion” in this context.

In a cylindrical geometry, the profiles of the electric field and potential created by the doping-related contribution are given by simple expressions,

$$F^{dop}(r) = \frac{qN_{dop}}{2\varepsilon_0\varepsilon_s}\cdot\left[-r+\frac{(R_0+w)^2}{r}\right],\ R_0<r<R_0+w, \quad (2a)$$

$$\varphi^{dop}(r) = \frac{qN_{dop}}{2\varepsilon_0\varepsilon_s}\cdot\left[-\frac{r^2-R_0^2}{2}+(R_0+w)^2\ln\frac{r}{R_0}\right]. \quad (2b)$$

Consequently, the contribution of the depletion layer charge to the full Si band bending is,

$$\varphi_s^{dop} = \frac{qN_{dop}}{2\varepsilon_0\varepsilon_s}\cdot\left[-\frac{w^2+2R_0w}{2}+(R_0+w)^2\ln\left(1+\frac{w}{R_0}\right)\right]. \quad (3)$$

The wave function of the ground mobile carrier state (b – variational parameter):

$$\psi = A(r-R_0)\exp\left(-\frac{b}{2}(r-R_0)\right),\ A^2 = \frac{b^4}{4\pi L(3+R_0b)}, \quad (4)$$

is normalized as $1=\int|\psi|^2 r\mathrm{d}r\mathrm{d}\alpha\mathrm{d}z$ for the region v given by $r=R_0\ldots\infty$, $z=0\ldots L$, angle $=0\ldots2\pi$.

The energy of a particle in the near-interface potential profile includes its kinetic energy T_r, the potential energy W^{dop} in a field of doping-related band-bending layer of width w, and the energy W^{well} of interaction with other mobile particles. The first two of the mentioned components are,

$$<T_r> = -\frac{\hbar^2}{2m}\int_v \psi\Delta_r\psi\mathrm{d}v = \frac{\hbar^2b^2}{8m}\cdot\frac{1+R_0b}{3+R_0b}, \quad (5)$$

$$\begin{aligned}<W^{dop}> &= q\int_v \varphi^{dop}(r)\psi^2\mathrm{d}v \\ &\approx \frac{3q^2N_{dop}}{2\varepsilon_0\varepsilon_s b^2(3+R_0b)}\left[\left(-10-6R_0b-R_0^2b^2\right)\right. \\ &\quad \left.+\left(1+\frac{w}{R_0}\right)^2\left(\frac{240}{R_0b}+30+2R_0b+R_0^2b^2\right)\right].\end{aligned} \quad (6)$$

Because of a presence of a ln function under the integral, only the approximate calculations are possible expanding $\ln(1+x)\approx x-x^2/2+x^3/3$. This expansion is justified because really only the range of small $z=r-R_0$ is integrated due to the exponent in the wave function. The expansion retaining only the first term would be too rough and the two terms not stable numerically.

The field created by mobile carriers themselves is found using Gauss's law exactly as,

$$\begin{aligned}F^{well}(r) &= \frac{qN_s}{\varepsilon_0\varepsilon_s}\frac{R_0}{r}-\frac{q(N_s2\pi R_0L)}{\varepsilon_0\varepsilon_s r}\int_{R_0}^{r}\psi^2(\tilde{r})\tilde{r}\mathrm{d}\tilde{r} \\ &= \frac{qN_sR_0}{2\varepsilon_0\varepsilon_s(3+R_0b)r}\left[b^3z^3+\left(3b^2+R_0b^3\right)z^2+\left(6b+2R_0b^2\right)z\right. \\ &\quad \left.+(6+2R_0b)\right]\exp(-bz).\end{aligned} \quad (7)$$

The corresponding potential profile can be obtained by integration of the above expression. It may be more convenient to perform integration in parts:

$$\begin{aligned}\varphi^{well}(r) &= \int_{R_0}^{r} F^{well}(\tilde{r})\mathrm{d}\tilde{r} \\ &= \frac{qN_sR_0}{\varepsilon_0\varepsilon_s}\ln\frac{r}{R_0}-\frac{q(N_s2\pi R_0L)}{\varepsilon_0\varepsilon_s}\left[\ln\frac{r}{R_0}\int_{R_0}^{r}\psi^2\tilde{r}\mathrm{d}\tilde{r}\right. \\ &\quad \left.-\int_{R_0}^{r}\psi^2\ln\frac{\tilde{r}}{R_0}\cdot\tilde{r}\mathrm{d}\tilde{r}\right].\end{aligned} \quad (8)$$

Again, with an expansion of logarithm, the well charge contribution to the surface potential is obtained by integrating until $r=\infty$:

$$\varphi_s^{well} \approx \frac{3qN_s}{\varepsilon_0\varepsilon_s b(3+R_0b)}\cdot\left[R_0b+2-\frac{10}{3R_0b}+\frac{40}{R_0^2b^2}\right] \quad (9)$$

To find the energy of interaction with this charge, the following integral is to be calculated, using the part-integration and the fact [8] that $\int_0^\infty x^n\exp(-ax)\mathrm{d}x = n!/a^{n+1}$: