The Dynamic Characteristics of the Field Emission from the Structures with Quantum Wells

V. Litovchenko, Y. Kryuchenko

► To cite this version:

V. Litovchenko, Y. Kryuchenko. The Dynamic Characteristics of the Field Emission from the Structures with Quantum Wells. Journal de Physique IV Proceedings, 1996, 06 (C5), pp.C5-141-C5-146. 10.1051/jp4:1996523 . jpa-00254402

HAL Id: jpa-00254402

<https://hal.science/jpa-00254402>

Submitted on 1 Jan 1996

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

The Dynamic Characteristics of the Field Emission from the Structures with Quantum Wells

V.G. Litovchenko and Y.V. Kryuchenko

Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, 45 Prospekt Nauki, Kiev-252028, Ukraine

Abstract. The dynamic characteristics of field electron emission from the layered structures with quantum wells have been qualitatively analysed. The main factor leading to appearance of the high frequency current oscillation is the negative differential resistance, observed under rather high electrical field. Layered structures with superthin barriers (like Si - SiO₂ - δ(Si) - SiO₂) seems to be likely to show this effect. The very narrow resonance peak in the FE-current from QW system at the definite external fields have been demonstrated.

INTRODUCTION

The steady state characteristics of the field electron emission (FE) from structures with quantum wells (QW) have been studied in some previous works [1-4]. The important characteristic of such a system is the occurrence of the nonmonotonous branches on the Fowler-Norgheim curves and, hence, occurrence of negative differential resistance $R_g < 0$, especially distinguished under resonance tunneling in QW systems. In such case the time oscillation of current, i.e. generation of current-voltage alternating signals with rather high frequency ω_{RT} have been predicted.

The estimation of ω_{RT} can be obtained, using the relation for electron of the energy level E_i oscillation in the quantum well:

$$\omega_{RT} \approx \pi \hbar e F / (2m_{\perp}^* E_i)^{1/2} \quad (1)$$

That means that for shallow QW and small effective mass of electron, the frequency of oscillations can be rather high. At reasonable electrical fields it may reach values, which is typical for tunneling processes ($> 10^{10}$ Hz).

1. THE MODEL AND CALCULATION OF FN-CURVES IN CASE OF RESONANCE TUNNELING

We considered the model shown in Fig.1. The variable parameters of the system were the electron density N_b in the bulk of the Si substrate, the thickness of the Si QW layer d_2 and the thicknesses of SiO₂ layers d_1 and d_3 . The fixed parameters were the dielectric constants of the semiconductor material $\epsilon_s = 11.7$ and of the insulator layer $\epsilon_i = 3.9$, the semiconductor-insulator band

discontinuity $\chi_{si} = 3.2$ eV, the insulator-vacuum affinity energy $\chi_{iv} = 0.95$, and the temperature $T = 293$ K.

The Fermi energy E_{Fb} for bulk electrons in the Si substrate, which are distributed over six equivalent ellipsoidal valleys in k-space, was determined using the following well known formula:

$$\pi^2 \hbar^3 N_b \nu^{-1} (2m_t^2 m_l)^{-1/2} (kT)^{-3/2} = F_{1/2}(E_{Fb}/kT) \quad (2)$$

where $\nu = 6$ is the degeneracy factor of the valleys in Si, $m_t = 0.19$ and $m_l = 0.92$ are the transverse longitudinal electron masses in these valleys, and $F_{1/2}$ is the Fermi integral of order one half. Formula (2) determines the position of Fermi level relatively to the conduction band bottom in the Si bulk. If the external electric field F is applied to the system then the band bending may occur at the surface of the Si substrate, depending on the electron density N_b . It leads to the appearance of a Space-Charge-Region (SCR) near the surface. Neglecting the influence of charged surface states (which was proven for conventional microelectronic technology) the total amount of electrons in the SCR per unit surface area is $N_s = F \epsilon_0 \epsilon_2 / (4\pi)$. If quantization of the electron states in the SCR takes place (this actually occurs at the high fields used in field emission applications) this density is expressed as the sum of the contributions N_i^j from all quantum levels E_i^j of the quantized electron states in the SCR (index i denotes the number of quantum level in the SCR, while j characterizes the type of valley from which the quantum level originates):

$$N_s = F \epsilon_0 \epsilon_2 / 4\pi = \sum_{i,j} N_{ij} = \sum_{i,j} n_i (m_{dj} kT / \pi \hbar^2) \times \ln \{ 1 + \exp[-(E_i^j - E_{Fs}) / kT] \} \quad (3)$$

where n_j is the degeneracy factor of the valleys of j type.

In the approximation of the triangular potential well, which is valid for the lowest quantum states in the SCR, the following analytical expression for discrete electron spectrum was used:

$$E_i^j = (\hbar^2 / 2m_{3j})^{1/3} [(3/2) \pi e (F / \epsilon_s) (i - 1/4)]^{2/3}, \quad i = 1, 2, 3, \dots \quad (4)$$

This formula gives the position of levels E_i^j relative to the conductive band bottom at the surface. Substitution of Eq.(3) into Eq.(2) allows one to determine the position of the Fermi level E_{Fs} in the SCR.

The emission current is determined by the sum of two contributions, $J = J_b + J_s$, where the bulk contribution J_b is the following :

$$J_b = \sum_j [em_{3j} kT / (2\pi^2 \hbar^3)] \int_0^\infty \ln \{ 1 + \exp[-(W - E_F) / kT] \} D_j(W) dW \quad (5)$$

where $D_j(W)$ is the transmission coefficient for the electron with the transverse energy W , $E_F = E_{FS}$ is the Fermi energy level which is common for the whole substrate including the SCR, and $W=0$ corresponds to the position of the conduction band bottom at the Si substrate surface. For the contribution from the quantum levels in the SCR we used the following formula from our previous work [3]:

$$J_s = \sum_j \sum_{i=1}^N [n_j (m_{dj}/\pi \hbar^2) kT] \times \ln\{1 + \exp[-(E_i^j - E_F)/kT]\} v_1^j D_j(E_i^j) \quad (6)$$

where v_1^j is the frequency of electron oscillations on the level E_i^j in the triangular SCR well.

The transmission coefficient D_j was calculated on the basis of numerical solution of the Schrödinger equation for the considered system, starting from the vacuum region with the wave function of the quasiclassical type

$$\psi_v = C \{2[W - eV(z)]\}^{-1/4} \exp[i \int_{z_0}^z dz \sqrt{2[W - eV(z)]}] , \quad (7)$$

and using the boundary conditions $\psi_+ = \psi_-$ and $(1/m_+)d\psi_+/dz = (1/m_-)d\psi_-/dz$ at the interfaces to obtain the continuous quantum flux. Here W is the transverse energy ($W=0$ corresponds to the position of conduction band bottom of the Si substrate surface), and $V(z)$ is the potential barrier.

Fig. 2 demonstrates the current/field characteristics in Fowler - Nordheim coordinates for the system with $N_b = 10^{19} \text{ cm}^{-3}$, $d_1 = d_2 = d_3 = 10 \text{ Å}$, and (100)Si orientation. In this case the degeneracy factor n_j for valleys with heavy m_{3j} electron mass ($j = 1$) is $n_1 = 2$, while with light m_{3j} mass ($j=2$) $n_2 = 4$; $m_{3j}(j=1) = 0.92$, $m_{3j}(j=2) = 0.19$.

In Fig. 3. the emission currents from the system with QW and without QW are compared for the case of $N_b = 10^{19} \text{ cm}^{-3}$ in both systems. It follows from this figure that the introduction of the additional QW layers leads to a substantial increase in emission current from the system at definite fields (when effective resonant tunneling occurs) and makes it possible to achieve emission currents even higher than from the system without such an additional layer. In the insert the relation of the current from the QW system to that from the system without QW is shown. It demonstrates that pronounced resonance peaks exist in the current from the QW system at definite external fields. The detailed calculation of RT -peak, Fig.2b, show the very narrow, monochromatic character (about $20\text{-}30 \text{ V cm}^{-1}$, $\Delta V \sim 10 \text{ mV}$). Also the appearing of the negative differential resistance have been demonstrated by Fig. 3.

2. SOME DYNAMIC CHARACTERISTICS.

Resonance tunneling, which can be realised in the double (or many) QW system, gives not only the negative resistance regime of FE-current (as has been demonstrated, in particular, in [4]), but also leads to specific enhanced kinetic properties as compared with single QW tunneling. In the case of resonance structures the tunneling time corresponds to the life-time τ_{RT} of the resonance

state as defined by Luryi [5]. The calculation of ω_{RT} on the base of a collision frequency with the walls of barrier, however, overestimates its value [6].

In [6] a rather concrete method for τ_{RT} estimation has been proposed by Choe et al. This so-called "Complex representation method for energy" took into account the energy levels in both of the QW's and the lifetime for the metastable states of a system. In a double QW system this is defined as

$$T = h/\Delta E_{ij} \quad (8)$$

where ΔE_{ij} is the spacing of the energy doublet in the coupled system.

For the GaAs-AlAs system, with $\phi_B = 210$ meV ($d_{QW} = 200$ Å, $d_B = 100$ Å), such a method gives the time of resonance tunneling $\tau_{RT} \approx 10$ ps (significantly less than the 5000 ps predicted for nonresonance single QW system).

For the SCR QW case we have relation for $1/T$, which in fact has a same meaning as proposed by formulae (8), namely is the oscillation frequency in the QW :

$$\nu_{SCR} = eF / 2(m_z^* E_{ij})^{1/2} \propto CF^{2/3}/m_z^{*1/3} \quad (9)$$

For film QW structures:

$$\nu_F = e \phi_B / 2d_{QW} (m_z^* E_{ij})^{1/2} \propto E_{ij}^{1/2} / d_{QW} \quad (10)$$

If we adapt the Choe et al model to our case FE structure (taking into account differences in d_{QW} , d_B , m_z^* , ϕ_B , etc.) we obtain a value of the same order as value in [6] (due to narrower barriers for FE structures) i.e. $\nu_F \approx 10^{11}$ Hz.

That means, that these systems have a frequency oscillation at resonance tunneling order 0.1 THz, i.e. values are very high.

The curves illustrating the field dependences of the ω_F , are shown on Fig. 4.

To solve the problem of real generation of the alternating FE current such an order of frequency it is important to consider the electrical circuit parameters of resonator, i.e. the capacitance and negative resistance values. So to achieve the indicated above superhigh values of ω , we have to choose materials with rather small z-effective mass m_z^* , ($\omega \sim m_z^{*-1/3}$), as well as to use not very narrow and deep QW as well as high electric fields F.

CONCLUSION

The analysis for frequency parameters of the field emission structures with quantum wells has been performed. Especially high parameters of generation of the field current oscillation take place under resonance tunneling (TeraHerz frequencies). Estimation relating to structures of practical interest have been made.

Acknowledgments

This work was supported by ISRF-96, CRDF N849

References

- [1] V.G. Litovchenko, Yu.V. Kryuchenko, *J. Vac. Sci. Technol.*, **B11(2)** (1993) 362.
- [2] V.G. Litovchenko, Yu.V. Kryuchenko, L.I. Il'chenko, *J. Micromech. & Microeng.*, **3** (1993) 74.
- [3] L.I. Il'chenko, Yu.V. Kryuchenko, V.G. Litovchenko, *Appl. Surf. Sci.*, **87/88** (1995) 53.
- [4] Yu.V. Kryuchenko, V.G. Litovchenko, *J. Vac. Sci. Technol.*, **B14(3)** (1996) 1.
- [5] S. Luri, in: *High Speed Semiconductor Devices*, ed. by Sze (NY, 1990) p.225.
- [6] W. Choe et al., *J. Appl Phys.* **79(10)** (1996) 7510.

Fig. 1. Band structure of the field emitting layered structure (Si-SiO₂-Si-SiO₂-vacuum)

Fig. 2. a) Fowler-Nordheim current for some structures: 1) $d_1=d_2=d_3=10\text{\AA}$; 2) $d_1=0, d_2=0, d_3=20\text{\AA}$. On insert is the normalized two QW current to current of the single QW system. b) Calculation of RT peak at small steps of 1) $\Delta F=10^5 \text{ Vcm}^{-1}$; 2) 10^4 Vcm^{-1} ; 3) 10^3 Vcm^{-1} .

Fig. 3. Resistance dependence of the field emitting layered structure versus applied voltage V (field strength) under resonance tunneling (for parameters Fig. 2a, 1).

Fig. 4. Frequency of the field emission current oscillations in field emitting structures under different transverse effective masses.