The modeling of calculations of thermodynamic and electronic parameters of hot electrons in a quantum well

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***Abstract*—** The heating of charge carriers in a quantum well was studied. The calculations of thermodynamic and electronic parameters: concentration, energy, chemical potential, heat-capacity and thermo electromotive force of hot two-dimensional electron gas in a quantum well in the energy region near or below the threshold for emission of optical phonon under the assumption that below this threshold an electron temperature can be defined, had been modeled. The obtained equations describe the dependence of heat-capacity and thermal electromotive force on a film thickness and an electron temperature in a good manner. It was determined that the acquired results calculated for the model under consideration, strongly differed from the results calculated on the base of a Maxwell distribution function.

***Keywords*—** chemical potential, concentration, heat-capacity, hot electrons, quantum well, thermal electromotive force.

I. Introduction

Semiconductor devices utilizing heterostructure have been actively developed as semiconductor growth technology such as the molecular beam epitaxy (MBE) are being advanced. Active researches are in progress on the phenomena of absorbing or emitting lights in the range of infrared caused by electron transitions between quantum-confined states of electrons or holes in the structures of quantum wells, quantum wires, or quantum dots due to the energy band line-up of the semiconductor hetero junction structures, and on the resonant tunneling effect of electrons through quantum-confined states, and on the significantly rapid electron moving effect of hot-electrons in the heterostructure [1].

Under certain conditions electrons in a semiconductor become much hotter than the surrounding crystal lattice. When this happens, Ohm's Law breaks down current no longer increases linearly with voltage and may even decrease. Hot electrons have long been a challenging problem in condensed matter physics and remain important in semiconductor research. Recent advances in technology have led to semiconductors with submicron dimensions, where electrons can be confined to two (quantum well), one (quantum wire), or zero (quantum dot) dimensions. In these devices small voltages heat electrons rapidly, inducing complex nonlinear behavior; the study of hot electrons is central to their further development [2].

Hot electrons have an effective energy larger than the thermal Fermi energy $\kappa_0 T_l$ with T_l the lattice temperature. A single volt across present-day submicron semiconductor devices introduces an electric field above 10^4 V/cm, which is generally enough to create hot electrons. Carrier heating occurs through an applied electric field, an externally applied photon field called optical pumping, multi-particle recombination processes and through stimulated emission. The same carriers cool down, i.e. dissipate energy, by emitting phonons, exciting other electrons through various scattering mechanisms, and also by emitting photons. The actual contribution of the emitted photons to the average energy of the electron ensemble thus depends on the emitted wavelength relative to the electron energy distribution function. Stimulated emission generally originates from around the band gap and therefore results in a net cooling of the electrons if it originates from the high energy band tail [3].

The behavior of semiconductor devices using any combination of the Hamiltonian equation for the classical mechanics, the Schrodinger equation for the quantum effects, the Boltzmann transport equation describing the carrier statistics and Maxwell's equations describing the electromagnetic [4]. The more exact combination and the specific application will determine the deviation between the modeled behavior and the actual device results. The device behavior involving hot electrons requires a description of the gain and the relaxation of the carrier's momentum and energy. It can be approximated by the deterministic hydrodynamic model, also known as the energy relaxation model. This model is an extension of the standard drift-diffusion model and introduces the electron temperature T_e for which one additional differential equation is added to the set of coupled non-linear differential equations [5]. Within this approach the physics are still described using parameterized carrier and energy properties like mobilities, diffusion constant and lifetimes, which now also depend on the electron temperature T_e [6].

In the given work the process of heating of charge carriers in a quantum well is considered while energy incident on the electronic gas from external field or light pumping. The energy of the depth order of the quantum well is transferred either to the lattice at optical phonons' emission or the electrons on lower levels of sized quantization. At sufficiently high concentration of electrons in sublevels of a quantum well

(surface concentration of charge carriers $N>10^{11}cm^{-2}$) the second process dominates which results in electrons' heating [7], [8]. The heating of electrons can essentially change light characteristics in the structures with a quantum well.

In our work the thermodynamic and electronic properties of hot electrons were theoretically studied at a lower level of a quantum well in the energy region near or below the threshold for emission of optical phonon under the assumption that below this threshold an electron temperature can be defined. At various values of a quantum well width the dependence of entropy, heat-capacity, thermal electromotive force (thermal e.m.f.) on an electron temperature was found. Besides the external electric field an electron-phonon scattering is also taken into account.

II. Distribution function

The electron temperature T_e is often used to describe a nonequilibrium electron gases in semiconductors, including the two-dimensional electron gas [9]. It is meaningful to define an electron temperature T_e which is higher than the lattice temperature T_l when the electron-electron scattering time τ_{ee} is smaller than the energy relaxation time to the lattice $\widehat{\tau}_L$. The electron temperature T_e can be determined from the balance equation $P=Q$, where P is the energy which the electron gas receives from the external field or through optical pumping, and Q is the energy transferred to the lattice by phonon scattering. In the case where there is scattering by optical phonons of energy $\hbar\Omega_0$ and T_e, $T_L \ll \hbar\Omega_0$, calculation of Q meets with special difficulties. This is true because in the energy region below threshold ($E<\hbar\Omega_0$), where emission of phonons is impossible, a temperature T_e can be defined even for low electron densities $n \gg n_c^-$, when $\tau_{ee} \ll \widehat{\tau}_A$ where τ_{ee} is the scale time of electron-electron scattering, specifying the rate of an electron-electron energy exchange, and $\widehat{\tau}_A$ is the scale time tor the energy relaxation of electrons with acoustic phonons. On the other hand, the region $E>\hbar\Omega_0$ determines Q. Therefore, in order to calculate Q when $n_c^+ \gg n \gg n_c^-$ it is necessary use the energy distribution function $f(E)$ above threshold, where deviates strongly from Maxwellian distribution which would define T_e. This problem first received attention in [10]. For the three-dimensional electron gas, Q was calculated in [11] and for the two-dimensional electron gas in [12].

We study here a layer of narrow-gap semiconductor with d thickness, inserted between two semi-infinite wide-gap semiconductors. A quantum well appears on a d layer for electrons. In such structures quantization occurs in the direction normal to the layers, allowing two-dimensional transport of electrons parallel to the layers. We assume extreme quantum limit conditions when the electrons occupy the lowest quantum level. Such conditions can be obtained for suitably chosen thicknesses of the well and at low temperature [13].

The energy spectrum of two-dimensional electron gas (TDEG) is supposed to be a parabolic one:

$$E_k = \frac{\hbar^2 k^2}{2m} + \frac{\hbar^2}{2m}\frac{\pi^2}{d^2} \quad (1)$$

$$E_0 = \frac{\hbar^2}{2m}\frac{\pi^2}{d^2}$$

It's supposed that the energy spacing between two lowest levels of the well

$$E_1 - E_0 = \frac{3\pi^2\hbar^2}{2md^2} \gg \hbar\Omega_0,$$

where $\hbar$ is the Plank's constant divided by 2π, $\vec{k}$ is the component of the electron wave vector parallel to the walls of the well, m is the effective mass, $\hbar\Omega_0$ – energy of an optical phonon.

When $\kappa_0 T_e \ll \hbar\Omega_0$, we can neglect all levels in the well except to the lowest.

We will assume that if there were no interactions with phonons all the electrons would be distributed according to a Maxwellian:

$$f(E) = (4\pi\ \mathrm{N}/\mathrm{P}_{Te}^2)e^{-E/Te} = f_{T_e}(E)$$

$$\hbar^2 P_{T_e}^2 = 2mT_e$$

$$E = E_k = \frac{\hbar^2 k^2}{2m}$$

$\hbar$

where κ is the Boltzmann constant, N – the number of electrons per 1cm^2 layer.

The lower critical density N_c^- does not depend on T_e, however, it does depend on the dimensions and shape of the well. For the square well, we have

$$N_c^- = \frac{1}{2\pi^2} p_0^2 \frac{\hbar/E_B}{\widehat{\tau}_A}\frac{2ms^2}{\hbar\Omega_0}$$

λ - determines the critical density N_c^+, higher which the distribution in $E>\hbar\Omega_0$ region differs from the Maxwell one and is defined by the formula.

$$\lambda = \pi^{-1/2}\frac{\tau_0}{\tau_{ee}}\left(\frac{k_0 T_e}{\hbar\Omega_0}\right)^{-1/2} = \frac{N}{N_c^+}$$

where τ_0 is emission time of an optical phonon.

For $\lambda \gg 1$ corrections to the distribution $f_{T_e}(E)$ are small for all $E-\hbar\Omega_0 \ll T_e\lambda^2$. Therefore the condition $\lambda=1$ determines the upper critical density of electrons

$$N_c^+ = \frac{1}{2\pi^{1/2}} p_0^2 \frac{\hbar/E_B}{\tau_0} \left(\frac{T_e}{\hbar\Omega_0}\right)^{1/2}$$

above which the distribution is close to Maxwellian even in the activated region $E > \hbar\Omega_0$.

For densities $N_c^- \ll N \ll N_c^+$, the distribution deviates strongly from $f_{T_e}(E)$ near and above threshold. For $\lambda \ll 1$

$$f(E) = \begin{cases} \sqrt{2\lambda}\, A\,; & |t| \ll \lambda,\ t=0 \\ 2\pi^{-1/2} A \lambda\, t^{-1/2} e^{-t}\,; & t>0,\ t \gg \lambda \\ A e^{-t} erf|t|^{1/2}\,; & t<0,\ |t| \ll \lambda \end{cases} \quad (2)$$

Here $t = \dfrac{E_k - \hbar\Omega_0}{k_0 T_e}$;

$$A = \frac{2\pi N\hbar^2}{m k_0 T_e} \exp\left(-\frac{\hbar\Omega_0}{k_0 T_e}\right) \quad (3)$$

Maxwell distribution in the vicinity of the threshold.

At threshold and in the immediate vicinity of threshold for $|t| \ll \lambda$ the distribution is smaller than $f_{T_e}(E)$, by a factor of $\lambda^{1/2}$. Above threshold $f(E)$ falls off within an energy interval T_e, as is true with $f_{T_e}(E)$, but it is smaller in amplitude.

III. ENTROPY AND HEAT-CAPACITY OF HOT ELECTRONS IN A QUANTUM WELL

Under this heading we calculated the thermodynamic parameters of hot TDEG in a quantum well. The state density corresponding to the spectrum (1) equals to:

$$g(E) = \sum_n \delta(E - E_k) = \frac{m}{\pi\hbar^2}\theta(E - E_1),$$

which itself presents a step function. The concentration of conductivity electrons is determined as:

$$N = \int g(E) f(E) dE$$

It can easily be shown that

$$N = \frac{\sqrt{2\lambda} m k_0 T_e}{\pi\hbar^2} \exp\left(\frac{\mu - \hbar\Omega_0}{k_0 T_e}\right); \quad t=0$$

$$N = \frac{2 m k_0 T_e}{\pi\hbar^2} \lambda \exp\left(\frac{\mu - \hbar\Omega_0}{k_0 T_e}\right)\left(erf\sqrt{c+1} - erf\sqrt{c}\right); \quad t>0 \quad (4)$$

$$N = \frac{\sqrt{2} m k_0 T_e}{\pi\hbar^2} \exp\left(\frac{\mu - \hbar\Omega_0}{k_0 T_e}\right)\left(erf\sqrt{2(c+1)} - erf\sqrt{2c}\right); \ t<0$$

$$N_m = \frac{m k_0 T_e}{\pi\hbar^2}\left(1 - \frac{1}{e}\right) \exp\left(\frac{\mu - E_1}{k_0 T_e}\right) \quad (5)$$

where

$$c = \frac{E_1 - \hbar\Omega_0}{k_0 T_e},$$

μ -chemical potential, (5) corresponds to a Maxwell distribution. According to (4) and (5) expressions the chemical potential is determined:

$$\mu = \hbar\Omega_0 + k_0 T_e \ln \frac{\pi N\hbar^2}{\sqrt{2\lambda} m k_0 T_e} \exp\left(\frac{\hbar\Omega_0}{k_0 T_e}\right); t=0$$

$$\mu = \hbar\Omega_0 + k_0 T_e \ln \frac{\pi N\hbar^2}{2 m k_0 T_e \lambda}\left[erf\sqrt{c+1} - erf\sqrt{c}\right]^{-1}; \ t>0 \quad (6)$$

$$\mu = \hbar\Omega_0 + k_0 T_e \ln \frac{\pi N\hbar^2}{\sqrt{2} m k_0 T_e}\left[erf\sqrt{2(c+1)} - erf\sqrt{2c}\right]^{-1}; \ t<0$$

$$\mu_m = k_0 T_e \ln \frac{\pi N\hbar^2}{m k_0 T_e}\left(\frac{e}{e-1}\right) \exp\left(\frac{E_1}{k_0 T_e}\right) \quad (7)$$

According to the chemical potential we may define the thermodynamic potential.

$$\Omega = -2\sqrt{2\lambda} N k_o T_e \exp\left(-\frac{\hbar\Omega_o}{k_o T_e}\right); \quad t=0$$

$$\Omega = -4N\lambda k_o T_e \exp\left(-\frac{\hbar\Omega_o}{k_o T_e}\right)\left(erf\sqrt{c+1} - erf\sqrt{c}\right); \ t>0 \quad (8)$$

$$\Omega = -2N k_o T_e \exp\left(-exp\left(-\frac{\hbar\Omega_o}{k_o T_e}\right)\left[\frac{1}{\sqrt{2}}\left(erf\sqrt{2(c+1)} - erf\sqrt{2c}\right) + e^{-c}\left(erf\sqrt{c} - \frac{1}{e} erf\sqrt{c+1}\right)\right]\right); \quad t<0$$

The main thermodynamic functions were calculated. The entropy calculated on the base of the thermodynamic potential (8) has the following view:

$$S = \sqrt{8\lambda} N k_0 (1 + \frac{\hbar\Omega_0}{k_0 T_e}) \exp(-\frac{\hbar\Omega_0}{k_0 T_e}); \quad t=0$$

$$S = \frac{2\lambda m k_0}{\pi\hbar^2} \exp(\frac{\mu_e - \hbar\Omega_0}{k_0 T_e}) \hbar\Omega_0 [erf\sqrt{c+1} - erf\sqrt{c}]; \quad t>0 \qquad (9)$$

$$S = \frac{m k_0}{\sqrt{2}\pi\hbar^2} \exp(\frac{\mu_e - \hbar\Omega_0}{k_0 T_e}) \hbar\Omega_0 [erf\sqrt{2(c+1)} - erf\sqrt{2c}] \quad t<0$$

For the calculation of heat-capacity we calculated the energy of electron gas:

$$E = N\sqrt{2\lambda}\ exp\ (-\frac{\hbar\Omega_o}{k_o T_e})(4E_1 + k_o T_e); \quad t=0$$

$$E = 4N\ \lambda k_o T_e exp(-\frac{\hbar\Omega_o}{k_o T_e})[(\frac{1}{2} + \frac{\hbar\Omega_o}{k_o T_e})(erf\sqrt{c+1} - erf\sqrt{c}) - \frac{1}{\sqrt{2}}(\sqrt{c+1}\,(e^{-(c+1)} - \sqrt{c}e^{-c}))]; \quad t>0 \qquad (10)$$

$$E = 2N\ k_o T_e exp(-\frac{\hbar\Omega_o}{k_o T_e})[\frac{1}{\sqrt{2}}(\frac{\hbar\Omega_o}{k_o T_e} + \frac{3}{8})(erf\sqrt{2(c+1)} - erf\sqrt{2c}) - e^{-(c+1)} erf\sqrt{c+1}\,(2 + \frac{E_1}{k_o T_e}) + e^{-c} erf\sqrt{c}(1 + \frac{E_1}{k_o T_e}) + \frac{1}{2\sqrt{\pi}}(\sqrt{c}\,(e^{-2c} - \sqrt{c+1}e^{-2(c+1)})]; \quad t<0$$

For heat-capacity the following equations calculated on the base of (9) were obtained:

$$C_v = \sqrt{2\lambda} N k_0 [1 + \frac{\hbar\Omega_0}{k_0 T_e}(1 + 4\frac{E_1}{k_0 T_e})] \exp(-\frac{\hbar\Omega_0}{k_0 T_e}); \quad t=0$$

$$C_v = \frac{2\lambda m k_0}{\pi\hbar^2} \exp(\frac{\mu_e - \hbar\Omega_0}{k_0 T_e}) \hbar\Omega_0 (\frac{1}{2} + \frac{\hbar\Omega_0}{k_0 T_e})[erf\sqrt{c+1} - erf\sqrt{c}] \quad t>0 \qquad (11)$$

$$C_v = \frac{m k_0}{\sqrt{2}\pi\hbar^2} \exp(\frac{\mu_e - \hbar\Omega_0}{k_0 T_e}) \hbar\Omega_0 (\frac{3}{8} + \frac{\hbar\Omega_0}{k_0 T_e})[erf\sqrt{2(c+1)} - erf\sqrt{2c}] \quad t<0$$

Basing on the obtained expressions the dependences of heat-capacity on a film thickness and an electron temperature were built [14], [15], [16]. In Fig.1 the heat-capacity curves of TDEG on the threshold of a quantum well on an electron temperature were given. The curve (a) corresponds to the heat-capacity of TDEG on the threshold, calculated on the base of a distribution function (2), and the straight one (b) to the heat-capacity, calculated on the base of a Maxwell distribution when the film thickness is d=100 A°. As it's shown in the Fig.1 the difference is essential.

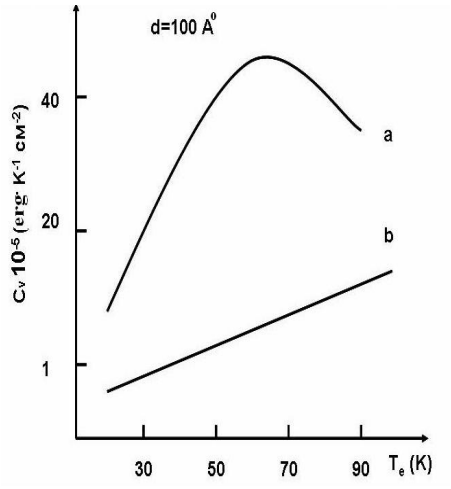


Fig. 1 dependence of heat-capacity on an electron temperature T_e at the film thickness d=100A°, a) on the threshold, b) on the base of a Maxwell distribution

In Fig. 2 the dependences of an electron heat-capacity TDEG on the threshold of a quantum well on the temperature at different values of film thickness are presented. With decrease in the film thickness the heat-capacity of TDEG at the threshold rises.

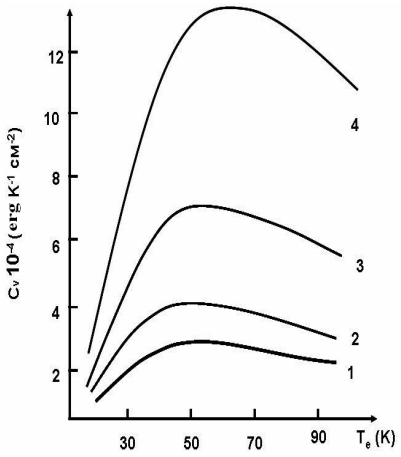
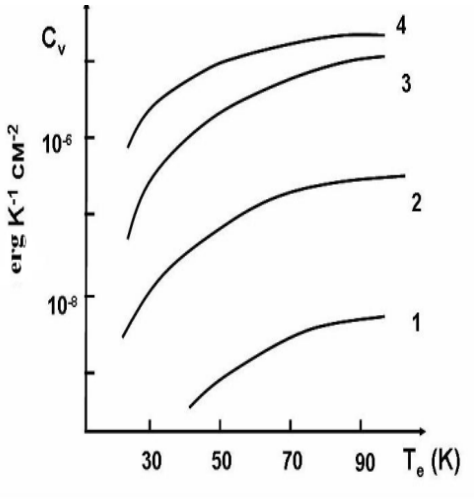
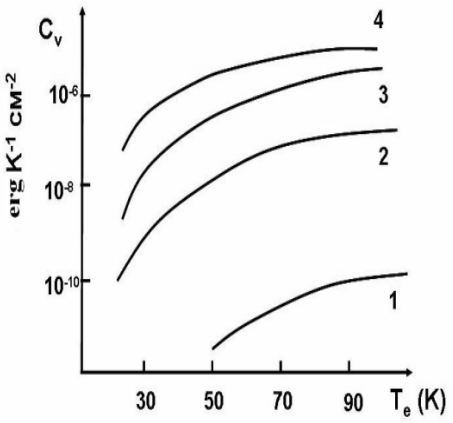


Fig. 2 dependence of an electron heat-capacity of TDEG on the threshold on the temperature T_e at the film thicknesses:
1. d=120A°, 2. d=100A°, 3. d=80A°, 4. d=60A°

In Fig. 3a and Fig. 3b the curves of the heat-capacity of TDEG higher than the emission threshold of an optical phonon and at a lower level of a quantum well in dependence with an electron temperature at different values of film thickness were presented which had been built correspondingly on the base of the expression (9). According to the Figures, with decrease in the film thickness, heat-capacity rises.



a)



b)

Fig.3 dependence of an electron heat-capacity of TDEG on the temperature T_e a) higher than the threshold, b) lower than the threshold at the film thicknesses: **1.** d=200A°, **2.** d=150A°, **3.** d=100A°, **4.** d=50A°

The results acquired on the base of the distribution functions (2) differ from the results acquired on the base of a Maxwell distribution (3) with T_e temperature (Fig. 4).

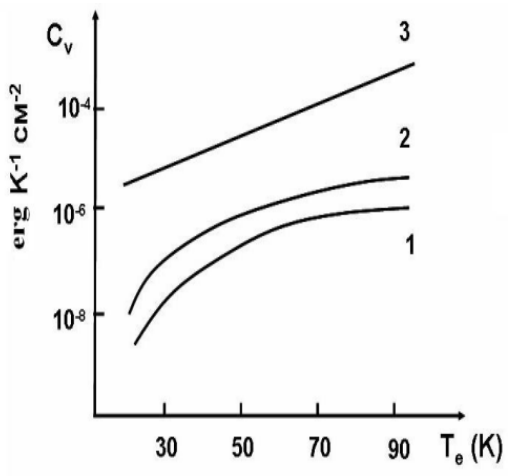


Fig. 4 dependence of an electron heat-capacity of TDEG on the temperature T_e at the film thicknesses d=100A°a) higher than the threshold, d) lower than the threshold, b) according to a Maxwell distribution

During building the curves the values of the parameters of a quantum well in GaAs N_c^+=1.7 ·10^{11} cm^{-2}, m=0.067·10^{-27}gr, $\hbar\Omega_0$= 10 meV [9], [10] were used.

IV.THERMO E.M.F. OF HOT ELECTRONS IN QUANTUM WELL

In the semiconductors, being in high electric fields, the study of thermal e.m.f. is of interest from the aspect of making detectors with the best parameters with their important advantages: low inertia, generally-recognized universality in the field of measuring several physical magnitudes, the opportunity of a remote control and others. Under the heading we studied the thermal e.m.f. of hot TDEG.

Let's assume that dimensional-quantum film with a type of carriers (conductivity electrons) is located in the electric field directed to its normals. The temperature gradient is on the plane of the film. In order to calculate the thermal e.m.f. we solve the non-collision kinetic equation and obtain the following expression

$$\alpha = -(\frac{1}{eT})\langle E-\mu\rangle \tag{12}$$

where the averaging sign has the following meaning

$$\langle\cdots\rangle = \frac{1}{n}\int(\cdots)G(E)(-\frac{\partial f}{\partial E})dE \tag{13}$$

Then we can write

$$\langle E-\mu\rangle=\frac{1}{2N(\pi\hbar)^2}\int f(E)(E-\mu)dP=\frac{m}{\pi N\hbar^2}\int(E-\mu)f(E)dE_{\perp}$$

Taking into consideration the distribution functions (2) and (3) the expression below is obtained:

1. On the threshold and direct vicinity off it $|t|<<\lambda$, $t=0$

$$\alpha=-\frac{\sqrt{2\lambda}}{eT_e}(k_0T_e-2\mu+2E_1) \tag{14}$$

where μ - chemical potential

$$\mu=k_0T_e\ln\frac{\pi N\hbar^2}{2m\lambda k_0T_e}\frac{\exp(\frac{\hbar\Omega_0}{k_0T_e})}{(erf\sqrt{c+1}-erf\sqrt{c})},$$

$$c=\frac{E_1-\hbar\Omega_0}{k_0T_e}$$

2. Higher than the threshold $t>0$, $t>>\lambda$

$$\alpha=-4\frac{k_0}{e}\lambda\exp(-\frac{\hbar\Omega_0}{k_0T_e})[(\frac{1}{2}+\frac{\hbar\Omega_0}{k_0T_e}-\frac{\mu}{k_0T_e})(erf\sqrt{c+1}-erf\sqrt{c})+\frac{1}{\pi}(\sqrt{c+1}e^{-(c+1)}-\sqrt{\frac{c}{\pi}}e^{-c})] \tag{15}$$

3. In a quantum well lower than the threshold $t<0$, $|t|<<\lambda$

$$\alpha=-2\frac{k_0}{e}\lambda\exp(-\frac{\hbar\Omega_0}{k_0T_e})[\frac{1}{\sqrt{2}}(\frac{\hbar\Omega_0}{k_0T_e}-\frac{\mu}{k_0T_e}+\frac{3}{8})(erf\sqrt{2c+1}-erf\sqrt{2c})+(\frac{E_1}{k_0T_e}-\frac{\mu}{k_0T_e}+1)e^{-c}erf\sqrt{c}-e^{-(c+1)}erf\sqrt{c+1}(2+\frac{E_1}{k_0T_e}-\frac{\mu}{k_0T_e})+\frac{e^{-2c}}{2\sqrt{\pi}}(\sqrt{c}-\frac{1}{e^2}\sqrt{c+1})] \tag{16}$$

4. For a Maxwell distribution:

$$\alpha_m=-2\frac{k_0}{e}\exp(-\frac{E_1}{k_0T_e})[(1-\frac{1}{e})(1+\frac{E_1}{k_0T_e}-\frac{e}{e-1}\ln\frac{\pi N\hbar^2}{mk_0T_e}\exp(\frac{E_1}{k_0T_e}))-\frac{1}{e}] \tag{17}$$

In Fig.5 the curves corresponding to a Maxwell distribution were built on the base of the expression (17) [16].

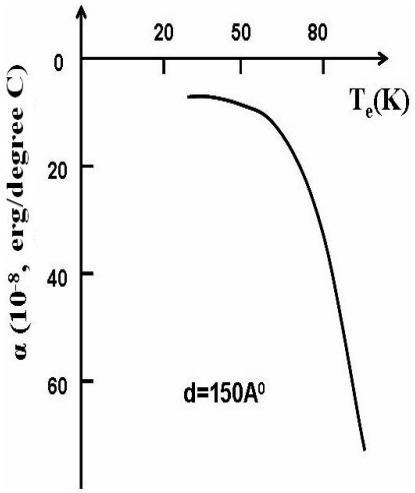
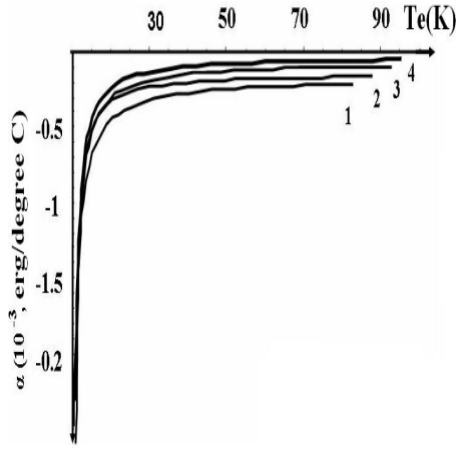
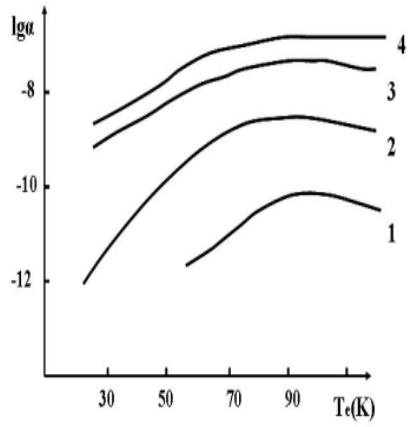


Fig. 5 dependence of thermal e.m.f. on an electron temperature at the film thickness d=150 A° on the base of a Maxwell distribution

The results obtained on the base of the distribution functions (2) differ from the results acquired basing on a Maxwell distribution. In Fig. 6 the dependence of thermal e.m.f. on an electron temperature was presented at several values of a film thickness, built according to the expressions (14), (15), (16). It can be concluded from the acquired results that with decrease in the film thickness, thermal e.m.f. decreases [17].



a)



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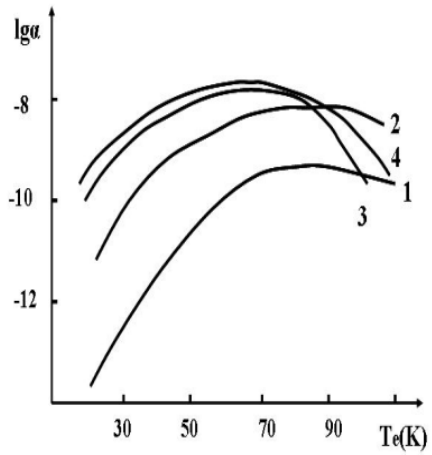

c)

Fig. 6 the dependence of thermal e.m.f. on an electron temperature at the film thickness: 1) d=50 A°, 2) d=100 A°, 3) d=150A°, 4) d=200 A° for the case of a quantum well a) on the threshold, b) higher than the threshold, c) lower than the threshold.

V. CONCLUSION

In the given work the distribution function for hot TDEG in a quantum well in the energy region near or below the threshold for emission of optical phonon under the assumption that below this threshold an electron temperature can be defined was chosen. The calculations of thermodynamic parameters and thermal e.m.f. of hot TDEG in a quantum well, formed in a quantum well depending on a film thickness and an electron temperature have been modeled. The results acquired on the base of a distribution function for hot TDEG at a lower level of a quantum well, in the region in the vicinity and higher the emission threshold of an optical phonon with the assumption that an electron temperature has been set lower than the threshold, differ from the results acquired basing on a Maxwell distribution. The difference is essential. It can be concluded from the obtained results that with the decrease in the film thickness, the heat-capacity of electrons rises, and thermal e.m.f. decreases. These results allow regulate the parameters for an optimal operation mode of devices on the base of heterojunctions.

REFERENCES

[1] "Hot-electron photo transistor", United States Patent 5977557, http://www.freepatentsonline.com/5977557.html.
[2] N.Balkan, "Hot electrons in semiconductors", Physics and Devices, pp.528, 1998.
[3] R. Hoskens, "Hot electron Injection laser", pp. 112, 2005.
[4] K.Hess, "Advanced theory of semiconductor devices", Prentice-Hall, 1988.
[5] T.G.van de Roer, "Microwave electronic devices", Champan and Hall, 1994.
[6] K.Hess, "Monte Carlo device simulation: full band and beyond", Kluwer Academic Publishers, 1991.
[7] L.Chenga, K.Ploga, "Molecular-Beam Epitaxy and Heterostructures", Moscow, «Mir», pp.584, 1989.
[8] E.Vorobyov, M.Y.Vinichenko, D.A.Firsov, V.L.Zerova, V.Y.Panevich, A.N.Sofronov, P.Tkhumrongsilala, V.M.Ustinov, A.E.Jikov, A.P.Vasilyev, L.Shterengas, G.Kipshidze, T.Hosoda, G.Belenky, "Charge carrier heating in quantum wells under optical and current injection of electron-hole pairs", Physics and technics of semiconductors, vol.44, 11, pp.1451-1454, 2010.
[9] S.E.Esipov, I.B.Levinson, Pisma Zh.Eksp.Teor.Fiz., vol.42, №5, pp.193-195
[10] N.B.Levinson, G.E.Mazhuolite, Zh.Eksp.Teor.Fiz, vol.50, pp.1048, 1966.
[11] B.L.Gelmont, R.I.Lyagushchenko, I.N.Yassevich, Sov.Phys.Solid.State, vol.14, pp.445, 1972.
[12] E.Esipov, I.B.Levinson. Journal of Experimental and Theoretical Physics, v.90, 1, 1986, pp.330-345
[13] D.Chattopadhyay, "Phys.Stat.Sol."(b), 119, K77, 1983.
[14] A.Mehrabova, T.G.Ismayilov, "Information on SPU Space Researches", pp.215-218, 1988.
[15] M.A.Mehrabova, "Information on SPU Space Researches", pp.180-1831989
[16] M.A.Mehrabova,"Thermodynamic and electronic properties of two-dimensional electron gas with heating", International Scientific Journal for Alternative Energy and Ecology, № 6, 86, pp.130-135, 2010
[17] M.A.Mehrabova, "Thermo-Electromotive Force of Hot Electrons in a Quantum Well", Polymer Networks Group, 20th Conference, Goslar, Germany, pp.146, 2010.

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