

ACTIVE MEDIA

PACS numbers: 42.55.Px; 41.75.Fr
DOI: 10.1070/QE2008v038n12ABEH013848

Excitation density distribution in electron-beam-pumped ZnSe semiconductor lasers

E.N. Donskoi, E.V. Zhdanova, A.N. Zalyalov, M.M. Zverev, S.V. Ivanov, D.V. Peregudov, O.N. Petrushin, Yu.A. Savel'ev, I.V. Sedova, S.V. Sorokin, M.D. Tarasov, Yu.S. Shigaev

***Abstract*. The spatial density distribution of the absorbed energy in ZnSe semiconductor lasers excited by electrons with energies from 2 keV to 1 MeV is calculated by the Monte-Carlo method. Approximate analytic expressions determining the absorbed energy of electrons in ZnSe are presented. The pump power threshold in a semiconductor quantum-well ZnSe structure is experimentally determined. The lasing threshold in such structures is estimated as a function of the electron energy.**

Keywords: *semiconductor laser, electron-beam pumping, electron energy, absorbed energy distribution, lasing threshold, quantum-well structure.*

Electron-beam-pumped semiconductor lasers allow obtaining monochromatic light in a broad spectral range [1]. Until now they have been fabricated from semiconductor single crystals and electron beams with the energy $E_0 = 250 - 300$ keV have been used to obtain high-power pulsed radiation [2]. In projection devices based on these lasers, E_0 was 50 – 70 keV [3, 4] and the current density I of electrons was $I > 10$ A cm^{-2}.

One of the reasons limiting the application of electron-beam-pumped semiconductor lasers is the high value of E_0 and the associated bremsstrahlung, whose intensity is $J \propto E_0^2 I$ [5]. Due to advances in the technology of producing quantum-well (QW) laser structures [6 – 9], the lasing threshold has been considerably decreased with respect to the quantities E_0 and I to the absolute safety level. Miniature electron-beam-pumped semiconductor lasers operating at $E_0 = 10$ keV have been manufactured [6, 7]. A record low threshold current density $I_{th} = 0.4 - 0.5$ A cm^{-2} was achieved at room temperature and $E_0 = 8 - 10$ keV in structures with a waveguide in the form of a superlattice and active region consisting of QWs with a fractional monolayer insertion of nanoislands enriched with CdSe [8, 9]. Due to the use of quantum-well multilayer structures in longitudinally-electron-beam-pumped scan lasers, the output power of several Watts was achieved and the working energy was decreased to 30 – 40 keV at room temperature [10, 11].

To increase the efficiency of electron-beam-pumped semiconductor lasers, its multilayer structure should be matched to the density distribution dE/dx of the absorbed energy of an electron beam dE/dx over the depth of the material. At the same time, unlike GaAs and CdS [1, 12], reliable results on the distribution dE/dx for ZnSe are scarce. Thus, for example, distributions dE/dx are presented in relative units with respect to the excitation intensity in papers [13, 14]. These data are inconsistent with the experimental dependences of the cathode luminescence intensity on the electron energy [15] and significantly differ from those obtained in this paper.

The aim of this work is to refine the dependence $dE/dx = f(E_0)$ and estimate the relation between I_{th} and dE/dx. In calculations and experiments, we used the same structure (Fig. 1) as in paper [9]. The 10-keV electron mean free path in ZnSe is fractions of microns. The experimental measurement of dE/dx for electrons with this energy presents some difficulties. Hence, to elucidate the dependence $I_{th} = f(E_0)$ in quantum-well electron-beam-pumped semiconductor lasers, the method is proposed for comparing experimental results on the excitation of these lasers by

E.N. Donskoi, A.N. Zalyalov, O.N. Petrushin, Yu.A. Savel'ev, M.D. Tarasov, Yu.S. Shigaev Federal State Unitary Enterprise 'Russian Federal Nuclear Center' – All-Russian Scientific Research Institute of Experimental Physics, prosp. Mira 37, 607190 Sarov, Nizhnii Novgorod region, Russia; e-mail: tarasov@expd.vniief.ru;
E.V. Zhdanova, M.M. Zverev, D.V. Peregudov Moscow State Institute for Radio-Engineering, Electronics and Automation (Technical University), prosp. Vernadskogo 78, 117454 Moscow, Russia; e-mail: mzverev@triniti.ru;
S.V. Ivanov, I.V. Sedova, S.V. Sorokin A.F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, ul. Politekhnicheskaya 26, 194021 St. Petersburg, Russia

Received 5 March 2008; revision received 12 August 2008
Kvantovaya Elektronika **38** (12) 1097 – 1100 (2008)
Translated by I.A. Ulitkin

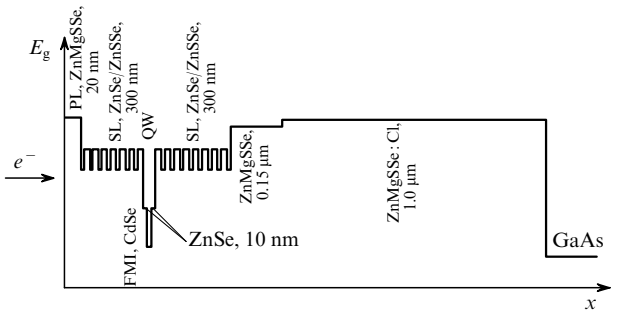

Figure 1. Scheme of a semiconductor structure: E_g is the energy gap width; e^- is the electron beam; PL is the protective layer; SL is the superlattice; QW is the quantum well; FMI is the fractional monolayer insertion.

electrons with a considerably higher energy E_0 with the calculations based on a reliable mathematic model, which makes it possible to determine experimentally the dependence dE/dx.

In experiments we used an accelerator arranged according to the scheme in [16], which allowed us to obtain electron pulses with the current density I up to 1 kA cm^{-2} and the current pulse FWHM $t_{0.5} = 2.5$ ns behind the accelerating tube window for the electron energy up to 0.4 MeV and the average electron energy $\bar{E}_0 \approx 0.3$ MeV in the spectrum.

The electron-beam-pumped semiconductor laser under study (Fig. 2) is mounted on a copper substrate with a 0.25-mm gap between 0.4-mm-thick copper plates, which are non-transparent for electrons. Transverse pumping geometry was used. Light from a Fabry–Perot resonator obtained by the cleavage method was focused on the input face of a step multimode silica–polymer optical fibre connected to the SNFT-8M photomultiplier with a nanosecond time resolution. A small-size Faraday cylinder measuring the current density and a calorimeter [17] from foil chromel–copel thermocouples detecting the dE/dx distribution in the material of this laser were placed near the laser. The average atomic number of the thermocouple material is $Z = 28$. The total thickness of each pair of the plates in the weld region was 7 μm and their average mass thickness x was 58 mg cm^{-2}. The accelerator electrons with the energy $E_0 = 0.03 - 0.4$ MeV penetrated to the depth of the calorimeter plates and the semiconductor material $x = 850$ mg cm^{-2} (Fig. 3). In this case, for the first values of x ($x \leqslant 116$ mg cm^{-2}) corresponding to the penetration depth of up to 14 μm, the distribution dE/dx was virtually uniform. Knowing the current pulse FWHM, we can determine the electron-beam power absorbed in the semiconductor. The electron current density in the sample plane decreased in vacuum with increasing the distance from the accelerating tube window.

The interaction of electrons with $E_0 \geqslant 0.002$ MeV was calculated by using the Monte-Carlo method according to the second version of the ELISA program [18]. The previous version of this program has been used for a long time in similar calculations with $E_0 \geqslant 0.01$ MeV [12]. The second version of the ELISA program is based on new libraries of interaction cross sections of γ quanta, electrons, and positrons with the matter, including new data on relaxation of atomic shells. These libraries were developed based on the

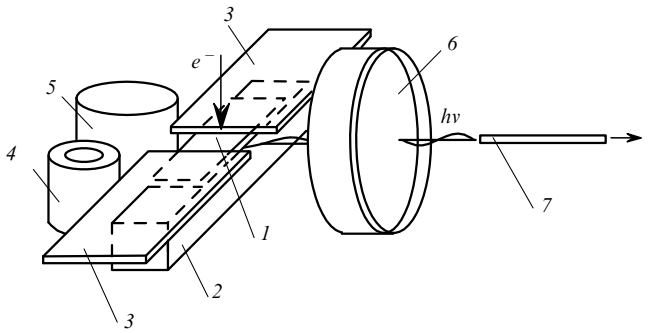

Figure 2. Scheme of the experiment: (*1*) electron-beam-pumped semiconductor laser; (*2*) copper substrate; (*3*) copper plates; (*4*) Faraday cylinder; (*5*) calorimeter; (*6*) lens; (*7*) optical fibre.

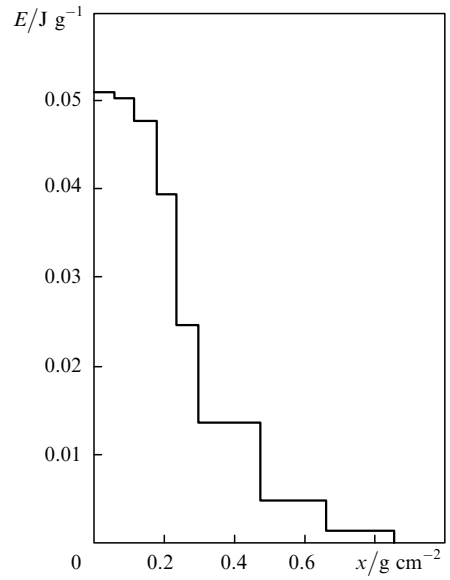

Figure 3. Distribution of the absorbed energy of the electron beam with the current density $I = 5.3$ A cm^{-2} in the calorimeter.

EPDL92 and EPDL97 libraries (γ quanta) [19, 20], EEDL92 (electrons) [21] and EADL92 libraries (relaxation of atomic shells) [22] distributed by the International Atomic Energy Agency [23] and on data for electrons and positrons from the literature.

The method itself was verified by comparing calculated values of dE/dx in air and in Al, Cu, Au and Pb samples with the experimental materials [24–27] for monoenergetic electrons with E_0 from 0.02 to 1 MeV. In all the cases, a part of which is presented in [12], the calculated and experimental results coincided within ±5 %–15 %.

The main part of the semiconductor structure (Fig. 1) consists of ZnSe ($Z = 32$) and ZnSSe ($Z = 26.7$). Calculations show that at low electron energies ($E_0 = 0.002$ MeV), the quantity dE/dx in the distribution maximum of ZnSSe is 10 % higher than that of ZnSe. When E_0 is increased, this discrepancy decreases significantly and for $E_0 = 0.03$ MeV it is less than 5 %. Based on this assumption, the absorbed energy of electrons within the structure containing ZnSe was calculated by assuming that it consists of pure ZnSe. The quatity of x was measured in g cm^{-2}, which was previously used in calculations of dE/dx by the Monte-Carlo method [28, 29]. To convert the quantity x in centimetres, it is sufficient to divide it by the density in g cm^{-3}, which for various semiconductor structures can noticeably differ from the density of the ZnSe single crystal [30].

The distributions dE/dx calculated by using a PC for $0.002 - 0.030$-MeV electrons incident along the normal to the surface of the semiconductor plate are shown in Fig. 4.

After approximations, we obtained that dE/dx can be represented in the same form as in paper [1]:

$$dE/dx = (dE/dx)_{max} f(\xi), \qquad (1)$$

where (dE/dx) are the energy losses in the distribution maximum; $\xi = x/x_0'$; x is the material depth from the semiconductor surface; x_0' is the quantity proportional to the free mean path of electrons; $f(\xi)$ is the density approximation of the energy losses normalised to unity.

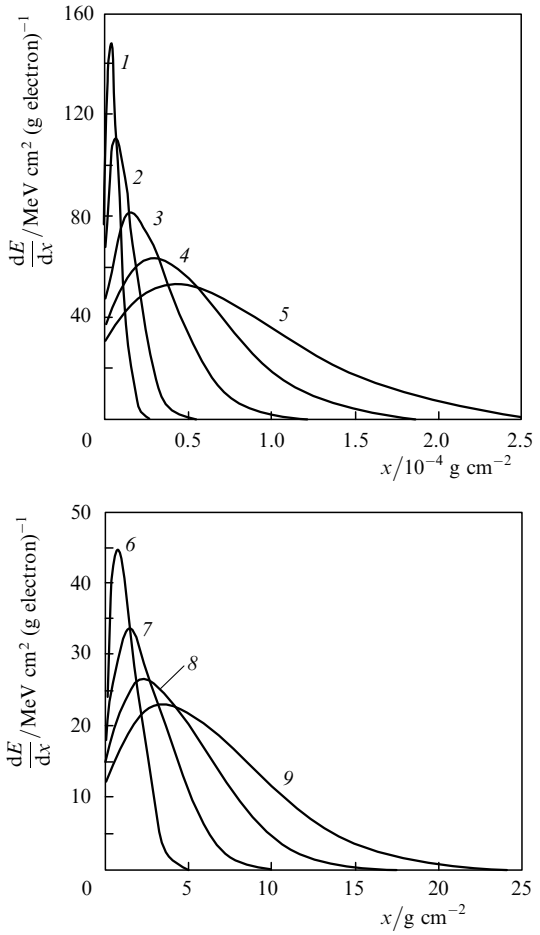

Figure 4. Distribution of energy losses over the ZnSe depth for $E_0 = 0.002$ (*1*), 0.003 (*2*), 0.005 (*3*), 0.007 (*4*), 0.009 (*5*), 0.012 (*6*), 0.018 (*7*), 0.024 (*8*) and 0.030 MeV (*9*).

The quantities entering Eqn (1) were found by using the method of least squares for $0.002 \leqslant E_0 \leqslant 0.03$ MeV with the deviation of no more than $\pm 5\,\%$ from the calculation:

$$(dE/dx)_{max} = 2.0981 E_0^{-0.6833}, \quad (2)$$

where $(dE/dx)_{max}$ is expressed in MeV cm^{-2} (g electron)$^{-1}$ and E_0 – in MeV,

$$f(\xi) = 0.52 \exp\left(13.94\xi - 93.1\xi^2 + 206\xi^3 - 184\xi^4\right), \quad (3)$$

$$x_0' = E_0\left[0.28(dE/dx)_{max}\right]^{-1}\left[1 - (E_0 + 3)^{-1.1}\right] \quad (4)$$

(x_0' is taken in g cm^{-2}).

For the electron energies $0.03 \leqslant E_0 \leqslant 1$ MeV, the approximation

$$(dE/dx)_{max} = 0.96 E_0^{-0.86} + 2.8 \quad (5)$$

is used instead of (2).

Expressions (1)–(5) allow one to determine the distribution of the absorbed electron energy in ZnSe without high-power PCs with special software.

By using the above approximation, the pump power distribution with respect to the crystal depth will be written in the form:

$$P_n(x) = 10^6 \times I_n (dE/dx)_{max} f(\xi), \quad (6)$$

where I_n (in A cm^{-2}) is the current density of electrons incident along the normal to the surface of the semiconductor material; P_n is expressed in W g^{-1}.

The experiments with the accelerator (Fig. 5) showed that the lasing threshold of this structure depended on the resonator length L, which indicates the smallness of nonresonator losses of light. For $L = 0.88$ mm the lasing threshold $I_{n\,th}$ was 5.3 ± 0.8 A cm^{-2}, which corresponds to the specific energy along the entire depth of the structure (up to the GaAs substrate) $E_{th} = 5.1 \times 10^{-2} \pm 0.8 \times 10^{-2}$ J g^{-1}. For the pulse duration $t_{0.5} = 2.5$ ns, the specific pump power threshold was $P_{th} = 2 \times 10^7 \pm 0.3 \times 10^7$ W g^{-1}.

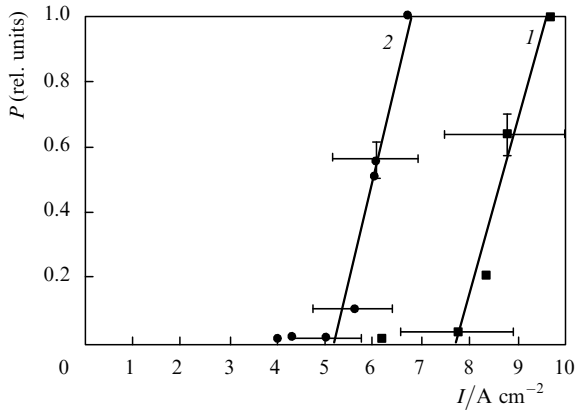

Figure 5. Dependences of the output power of the electron-beam-pumped semiconductor laser on the pump current density for the resonator length $L = 0.52$ (*1*) and 0.88 mm (*2*).

Taking (6) into account, we will calculate to what pump current density by a monoenergetic electron beam, the average value $\bar{P}_{th} = 2 \times 10^7$ W g^{-1} corresponds in the region whose boundaries are determined by the superlattice (Fig. 1):

$$\bar{P}_{th} = \frac{10^6 I_{n\,th}}{\Delta x} \int_{x_1}^{x_2} (dE/dx)_{max} f(\xi) dx. \quad (7)$$

Here, (for the material density $\rho = 5.27$ g cm^{-3}) $\Delta x = 3.12 \times 10^{-4}$ g cm^{-2} is the material thickness occupied by SL + QW + FMI (Fig. 1); $x_1 = 1.05 \times 10^{-5}$ g cm^{-2} is the coordinate of the SL beginning (after the protective 20-nm-thick layer); $x_2 = 3.32 \times 10^{-4}$ g cm^{-3} is the coordinate of the SL end.

According to calculations (Fig. 6), the minimal threshold current density $I_{n\,th} = 0.7$ A cm^{-2} necessary to obtain $\bar{P}_{th} = 2 \times 10^7$ W g^{-1} corresponds to the electron energy $E_0 = 0.015$ MeV. The increase in the density $I_{n\,th}$ in the region of lower electron energies is determined by losses in the protective layer and its increase in the region of higher electron energies is related to the decrease in $(dE/dx)_{max}$. The calculated threshold current density for the energy $E_0 = 0.015$ MeV agrees satisfactorily with the experimental quantities [8, 9]. For the electron energy $E_0 = 0.3$ MeV, which is equal to the average electron energy in the accelerator spectrum, $I_{n\,th} = 8$ A cm^{-2} (Fig. 6). The discrepancy with the experimental value (5.3 ± 0.8 A cm^{-2}) is

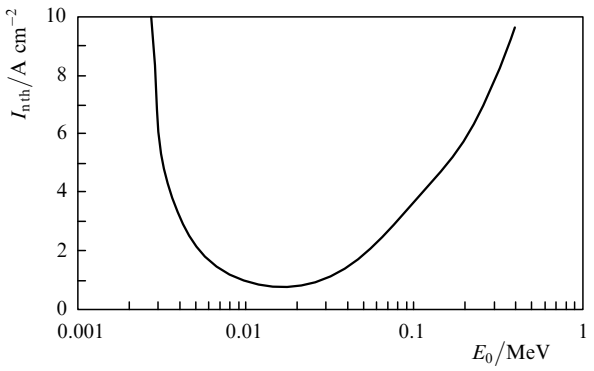

Figure 6. Calculated dependence of the threshold current density on the electron energy.

determined, first of all, by the presence of low-energy electrons in the accelerator spectrum.

Thus, the E_0 dependence of the threshold current density of highly-efficient quantum-well electron-beam-pumped semiconductor lasers is determined, first of all, by the spatial distribution of the pump energy. To determine accurately the excitation density for low values of E_0, it is necessary to take into account the diffusion of non-equilibrium carriers, which can change the initial distributions dE/dx. The effect of the carrier diffusion will be significant if the diffusion length is comparable with the penetration depth of electrons into the structure. The diffusion length in ZnSe structures is ~ 0.5 μm (2.6×10^{-4} g cm^{-2}) [31]. In this case, it is necessary to take into account the carrier diffusion if the pump electron energy does not exceed 10–20 keV. Then, the above expressions can be used as initial ones. For higher pump electron energies, the presented results can be directly used to estimate the threshold parameters and dimensions of semiconductor structures made of materials close to ZnSe in their average atomic number.

Acknowledgements. This work was supported by the ISTC (Project No. 3754).

References

1. Bogdankevich O.V., Darznek S.A., Eliseev P.G. *Poluprovodnikovye lazery* (Semiconductor Lasers) (Moscow: Nauka, 1976).
2. Bogdankevich O.V. *Kvantovaya Elektron.*, **21** (12), 1113 (1994) [*Quantum Electron.*, **24** (12), 1031 (1994)].
3. Olikhov I.M. *Elektronika: Nauka, Tekhnologiya, Biznes*, (3–4), 25 (1998).
4. Bogdankevich O.V., Meerovich G.A., Olikhov I.M. *Radiotekhn Elektron.*, **44** (8), 901 (1999).
5. Kharadzha F.N. *Obshchii kurs rentgenotekhniki* (Fundamentals of X-ray Engineering) (Moscow: Energiya, 1966).
6. Molva E., Accomo R., Labrunie G., Cibert J., Bodin C., Dang L.S., Fenillet G. *Appl. Phys. Lett.*, **62**, 796 (1993).
7. Herve D., Accomo R., Molva E., Vanzetti L., Paggel J.J., Sorba L., Francioci A. *Appl. Phys. Lett.*, **67** (15), 2144 (1995).
8. Zverev M.M., Ivanov S.V., Peregudov D.V., Sedova I.V., Sorokin S.V., Kop'ev P.S. *Kvantovaya Elektron.*, **34** (10), 909 (2004) [*Quantum Electron.*, **34** (10), 909 (2004)].
9. Zverev M.M., Sadchikhin A.V., Gamov N.A., Zhdanova E.V., Peregudov D.V., Studenov V.B., Ivanov S.V., Sedova I.V., Sorokin S.V., Gronin S.V., Kop'ev P.S. *Pis'ma Zh. Tekhn. Fiz.*, **33** (24), 1 (2007).
10. Basov N.G., Dianov E.M., Kozlovsky V.I., Krysa A.B., Nasibov A.S., Popov Yu.M., Prokhorov A.M., Trubenko P.A., Shcherbakov E.A. *Kvantovaya Elektron.*, **22** (8), 756 (1995) [*Quantum Electron.*, **25** (8), 726 (1995)].
11. Basov N.G., Dianov E.M., Kozlovsky V.I., Krysa A.B., Nasibov A.S., Popov Yu.M., Prokhorov A.M., Trubenko P.A., Shcherbakov E.A. *Laser Phys.*, **6** (3), 608 (1996).
12. Bogdankevich O.V., Donskoi E.N., Kovalenko V.A., Panitkin Yu.G., Tarasov M.D. *Kvantovaya Elektron.*, **10** (11), 2236 (1983) [*Sov. J. Quantum Electron.*, **13** (11), 1453 (1983)].
13. Trager-Cowan C., Yang F., O'Donnell K.P. *Adv. Mater. Optics and Electronics*, **3**, 295 (1994).
14. Trager-Cowan C., Bagnall D.M., McGow F., et al. *J. Crystal Growth*, **159**, 618 (1996).
15. Zverev M.M., Peregoudov D.V., Zdanova E.V., Gamov N.A., Studionov V.B., Ivanov S.V., Sorokin S.V., Sedova I.V., Kopev P.S., Le-Si-Dang. *14 Int. Symp. «Nanostructures: Physics and Technology»* (St.-Petersburg, 2006) p. 27.
16. Belkin N.V., Tarakanov M.Yu., Tarasov M.D. *Prib. Tekhn. Eksp.*, (6), 133 (1987).
17. Suchkov V.P., Tarasov M.D., Shcherbak Yu.P. *Prib. Tekhn. Eksp.*, (5), 58 (1987).
18. Donskoi E.N. *Sb. Dokl. VI Mezhd. Konf. po Radiotsionnoi stoikosti* (Proc. Seminar VI Int. Conf. On Radiation Resistance) (Sarov: RFNC-VNIIEF, 2003) p. 93.
19. Cullen D.E., Chen M.H., Hubbell J.H., Perkins S.T., Plechaty E.F., Rathkopf J.A., Scofield J.H. *LLNL, Report UCRL-50400*, **6**, Rev.4 (October, 1989).
20. Cullen D.E., Hubbel J.H., Kissel L. *LLNL, Report UCRL-50400*, **6**, Rev. 5 (September, 1997).
21. Cullen D.E., Perkins S.T., Seltzer S. M. *LLNL, Report UCRL-50400*, **31** (November 1991).
22. Perkins S.T. et al. *LLNL, Report UCRL-50400*, **30** (October, 1991).
23. Cullen D.E., Chen M.H., Hubbell J.H., Perkins S.T., Plechaty E.F., Rathkopf J.A., Scofield J.H. *LLNL, Report IAEA-NDS-158* (September 1994); http://www-nds.iaea.org/EPDL97/.
24. Von A., Grun E.Z. *Naturf.*, **12a** (2), 89 (1957).
25. Cosslett V.E., Tomas R.N. *Brit. J. Appl. Phys.*, **15** (8), 883 (1964).
26. Cosslett V.E., Tomas R.N. *Brit. J. Appl. Phys.*, **16**, 779 (1965).
27. Nakai Y. *Jpn J. Appl. Phys.*, **2** (12), 743 (1963).
28. Baranov V.F. *Dozimetriya elektronnogo izlucheniya* (Dosimetry of Electron Radiation) (Moscow: Atomizdat, 1974).
29. Kol'chuzhkin A.M., Uchaikin V.V. *Vvedenie v teoriyu prokhozhdeniya chastits cherez veshchestvo* (Introduction to the Theory of Propagation of Particles Through the Matter) (Moscow: Atomizdat, 1976).
30. Babichev A.P., Babushkina N.A., Bratkovskii A.M., et al. *Fizicheskie velichiny: Spravochnik* (Handbook of Physical Quantities) (Moscow: Energoatomizdat, 1991).
31. Kozlovsky V.I., G.Sadofyev Yu. *J. Vac. Sci. Technol. B*, **18** (3), 1538 (2000).