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EXPERIMENTAL DATA GENERALIZATION OF DELTA ELECTRON YIELD INDUCED BY HIGH ENERGY ELECTRON INTERACTION WITH AMORPHOUS AND SINGLE-CRYSTAL TARGETS

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The generalized experimental results of delta electron yield obtained at the NSC KIPT electron accelerators in the energy range from 0.5 MeV to 1.6 GeV are presented. Thin foils of Be, Al, Si, Ni, and Nb were used as experimental targets. It was established in general that delta electron yield is proportional to the product √T·Z/A, where T is the thickness of the sample in g/cm^2 and it has a linear dependence. It is shown that the main factor of delta electron yield increasing is not primary beam energy, but the electron density of the experimental target.

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INTRODUCTION

During the research of electron beam interaction with amorphous and single-crystal thin targets, it is important to obtain universal dependencies that would make it possible to estimate and predict the delta electron yield concerning the primary electron beam energy, the experimental target thickness, and Z.

Well known that delta electron interaction with a matter induced during primary particle beam irradiation material (as secondary particles) plays a significant role in the irradiation effect accumulation (radiochemical effects, density effect, and polarization materials, etc.) in comparison with low energy secondary electrons emitted from surface samples. The main reasons are the changing of the initial electron energy distribution of secondary particles along the penetration direction of the primary electron beam in the solid state plasma under target irradiation due to pair and collective interactions due to its energy losses.

For example, this knowledge about SEY data values and energy spectrum information is necessary for many areas of applications for technology and science: accelerated particle beam monitor development, prediction of satellite electronic components operation stability during space irradiation, an understanding of beam plasma discharges and behavior of plasmas and the electron interaction with surfaces, optimization of the imaging conditions for electron microscopy, providing information about the electronic structure and surface properties of materials in surface analysis, optimization of the exposure conditions in electron beam lithography etc.

In general, the experimental problem is consisting of routine measurement of delta electron yield from several targets (thin foils, or gas targets) with different thickness (the primary electron beam absorption of cause should be neglected) for huge range of primary electron energy. The energy scale of primary electron beam is important for analysis of SEY because ionization losses versus beam energy gas a very specific conduct and has local minimum when the velocity of primaries close to velocity of light [1].

1. EXPERIMENTAL TECHNIQUE DESCRIPTION

A detailed description of the experimental facility for measuring delta electron yield during high energy electrons passing through thin foils was presented in Ref. [2]. The single foil monitor system as like base of the experimental technique was chosen and in general schematically it is presented in Fig. 1. The proposed and developed measuring system "collector – thin target – collector" (C1-emitter-C2) has a unique possibility for registration low energy secondary electron emission from the front, the back surface of the experimental target and also delta electron yield independently. The detail description and experimental possibilities of secondary electron emission measurement technique were presented in [1].

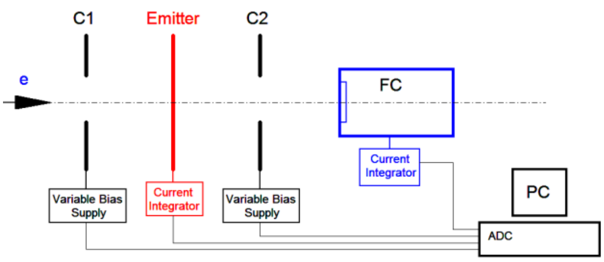

Fig. 1. General schematic view of SEY measurement on the high energy beam passing through thin foil. C1 and C2 – collectors (isolated electrodes connected to independent variable bias supplies with voltage range -70…+70 V). Secondary electron emission current was measured by developed current integrator [3]. Primary electron beam stability was controlled by complete absorption Faraday cup

The PC application permits the realization of an automatic mode of measuring the secondary emission coefficients depending on the electric potentials on the collectors (C1 and C2) and the operating modes of the electron accelerator (while changing the energy and current of the primary beam for example), as well as to carry out the initial processing of the obtained experimental data.

Typical voltage current characteristics were presented in Fig. 2. In this paper, the main attention was paid to the delta electron yield, which corresponds to the part of the current-voltage characteristic at retarding potential values region. As shown in Fig. 2 the delta electron yield does not depend on the value of the retarding potential less than – 20 V for three cases of measured voltage current characteristics, when secondary electron emitting for front and back surface (C1+C2), front surface (C1) and back surface (C2).

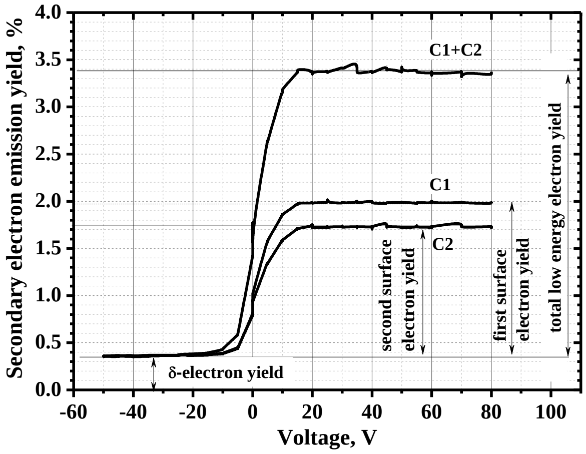

Fig. 2. SEE Yield dependences versus retarding and extraction voltage from surfaces of 8 μm Al foil, primary electron energy is 15 MeV [4]

The general information about delta electron yield which was presented in the references and measured by single thin foil technique are represented in Table. For general systematization of experimental data of different research group (and experimental measurements) authors was proposed to use electron density normalization. Main idea is find the universal dependence of delta electron yield for different experimental condition such like thin target thickness, chemical elements, and primary electron beam energy. In the Table the experimental data such target thickness T in μm was recalculate to equivalent values in g/cm^2 with application of data about material density and after was found resulting multiplication of expression $T^{0.5}\cdot Z/A$, where Z – atomic number and A – relative atomic mass.

Thus, delta electron yield depends only on the target thickness and the electron number of atom, which is proportional to the sample electron density. As can be seen from the presented data on the Fig 3, the dependence of the delta electron yield versus the energy is not observed experimentally. The entire set of experimental points of generalized experimental yields Y_g were with a straight line of the following formula (1):

$$Yg \approx 0.2 \cdot T^{0.5} \cdot Z / A, \qquad (1)$$

where T is the target thickness, g/cm^2; Z is atomic number and A is relative atomic mass of the thin foil target respectively.

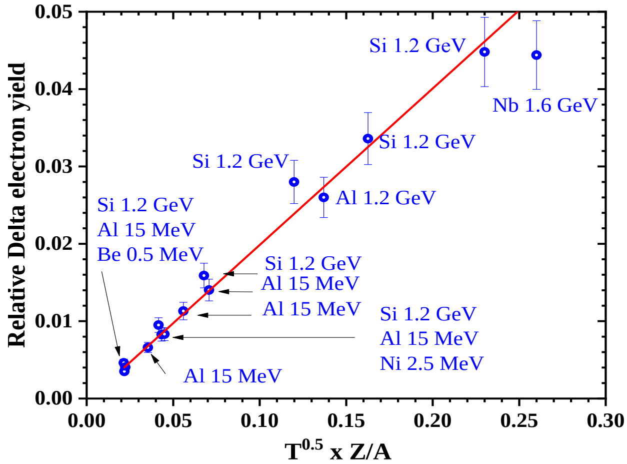

Fig. 3. Delta electron yield versus $T^{0.5}\cdot Z/A$

Proposed expression gives a possibility to predict the delta electron yields from the experimental targets with an accuracy of 5%, taking into account the target material, its thickness and material. This statement is, of course, relevant for the case when the primary electron beam absorption can be neglected. The proposed fitting model has several features. First of all, the straight line goes to zero, which physically corresponds to the model of charge particle beam interaction of with thin foils: yield of secondary particles is proportion to the relative concentration of atoms in the target. Second one is the relative concentration of initial electrons in the target depends the Z/A.

The largest deviations of delta electron yields are observed in the region of $0.15 \leq T^{0.5}\cdot Z/A \leq 0.25$. Perhaps this is related to the uniqueness of the samples that were used in the experiments – monocrystalline Si and Nb. In their study, the main goal was to determine the effect of orientation on the delta electron yield. They are the only ones represented in Fig. 2 and Table. They were single crystals, compared to the others – amorphous. Another uncontrolled effect was present during the experimental research is the target temperature. Procedure of target temperature control is very difficult for realization during experiment. The non-contact technique (for IR pyrometer) application has a limit of background radiation condition in the bunker of electron linear accelerator. The contact technique with thermocouple application makes it difficult to measure the electron current of secondary electrons from the thin foil (two measuring electric circuit ability). Preliminary data from the simulation of foil heating by an electron beam showed that a minor effect of electron beam heating is present but does not play an important role in the processes of secondary emission for foil thicknesses up to 100 μm and primary electron beam energy up to 30 MeV [5]. Perhaps the difference in the delta electron yield is precisely related to the discrepancy between the target thickness of and its electron density.

In the region of $T^{0.5}\cdot Z/A \leq 0.15$, points that are close or coincide are observed on the Fig. 3, although targets with different Z were used. This only proves that by changing the target thickness with different Z, it is possible to obtain a target with approximately the same specific concentration of electrons (relative electron density). That is, the delta electron yield will have a close value. It was this assumption that became the basis for compiling the total set of experimental data for different conditions of the experiment (energy of the primary beam, thickness of the target, and Z).

As a result, the ideal target selection parameter for delta electron yield measurement is not the target thickness or the atomic number of a chemical element, but rather the specific electron density. Since the yield of delta electrons depends on their quantity in the given elementary volume of the experimental sample when considering pairwise interactions.

It should also be taken into account that there are differences in the background conditions for different experiments. The main problem in the research of secondary electron emission using the proposed technique is not so much in vacuum conditions as the presence of background secondary electrons formed during the interaction of the primary beam with the residual gas in the vacuum beam transport system. Accordingly, the absorption of background low-energy electrons by the target in the presence of electric potentials on the collectors affects the reliability of measuring the delta electron yield from the target. In fact, options are possible when application of long transportation systems (with a vacuum below 10^{-6} Pa) in front of the experimental target, an additional gas target will already be formed from residual gas, which will also be a source of secondary electrons. It is this fact that should be taken into account when performing experiments and processing their results.

Delta electron yield from "thin" Be, Al, Si, Ni, Nb foils versus primary electron beam energy (energy range up 0.5…1600 MeV)

$T^{0.5}\cdot Z/A$	Chemical element and E_p	T, µm	T, g/cm^2	Z/A	T·Z/A	Delta Yield	Ref.
0.0214	Si 1.2 GeV	8	0.00184	0.5	0.00092	0.0046	[6]
0.0224	Al 15 MeV	8	0.00216	0.481481	0.00104	0.0041	[4, 8]
0.0218	Be 0.5 MeV	13	0.002405	0.444444	0.001069	0.0035	*
0.0354	Al 15 MeV	20	0.0054	0.481481	0.0026	0.0066	[4, 8]
0.0415	Si 1.2 GeV	30	0.0069	0.5	0.00345	0.0095	[6]
0.0433	Al 15 MeV	30	0.0081	0.481481	0.0039	0.0083	[8]
0.0450	Ni 2.5 MeV	10	0.0089	0.477002	0.004245	0.0083	*
0.0559	Al 15 MeV	50	0.0135	0.481481	0.0065	0.0113	[4, 8]
0.0678	Si 1.2 GeV	80	0.0184	0.5	0.0092	0.0159	[6]
0.0708	Al 15 MeV	80	0.0216	0.481481	0.0104	0.0140	[4]
0.1199	Si 1.2 GeV	250	0.0575	0.5	0.02875	0.0280	[6]
0.1370	Al 1.2 GeV	300	0.081	0.481481	0.039	0.0260	[9]
0.2600	Nb 1.6 GeV	408	0.349	0.441	0.1541	0.0444	[7]
0.1626	Si 1.2 GeV	460	0.1058	0.5	0.0529	0.0336	[6]
0.2300	Si 1.2 GeV	920	0.2116	0.5	0.1058	0.0448	[6]

*Experimental data was obtained by ELIAS Van de Graaf Accelerator of NSC KIPT, not published.

2. CROSS-SECTION OF DEL TA ELECTRON GENERATION

In the ref [4], an estimate of the delta electron generation cross section was previously given when applying thin aluminum foil from 8 to 100 µm thickness. The general idea of the proposed approach is based on that delta electron yield increases with the target thickness for a constant energy of the primary beam. In this case, it was possible to obtain an estimate of the cross-section value. Accordingly, it should be considered that there are certain restrictions on its application since the foil thickness is a critical parameter. When using too-thick targets, a significant contribution will take place by the absorption of not only secondary electrons but also the absorption and growth of the root-mean-square scattering values of the primary electron beam. Such types of experimental conditions are result in a deterioration of the experimental data certainty. The use of thin foil in the experiment of less than 8 µm, respectively, requires the application of measuring equipment with increased sensitivity and an increase in experimental time. According to the authors, the proposed approach is optimal for evaluating (determining) the average cross-section value. But in our case necessary to take into account two processes: generation and absorption of secondary electrons, respectively. The fitting procedure only makes it possible to give an estimate of the average cross-section for target thickness less than 8 µm. It, accordingly, allows neglecting the effects of absorption and scattering of primary and secondary electrons.

To estimate the average cross-section of generation and absorption of delta electrons for the cases presented in Table, it was necessary to change the measurement units of g/cm^2 to the value of the electron density of the sample: number electrons per cm^2. In this way, the versatility of the fitting procedure results is ensured.

Taking into account the above, the cross-section calculation formula (ref. [4]) has the following form:

$$\sigma = \frac{I_s}{I_p \cdot L \cdot \rho} = \frac{\delta}{L \cdot \rho} = \frac{\delta \cdot A}{L \cdot \rho \cdot N_A \cdot Z}, \qquad (2)$$

where $\delta = I_s/I_p$ – electron emission coefficient (in our case only delta electron yield; I_s – current of secondary electrons; I_p – current of primary electron beam measured by FC); L – target thickness, cm; ρ – target density, g/cm^3; δ – cross-section, cm^2; A – atomic number of target (1/mole); Z – periodical number of target chemical element; N_A – Avogadro constant.

As a result, by simple calculations, the dependence of the cross-section of the generation and absorption of secondary electrons (delta-electrons) was determined depending on the electron density of the experimental sample. Calculated data of average cross-section is presented in Fig. 4. A logarithmic scale was chosen for greater convenience in the analysis of the obtained data. The fitting of the calculated dependence was done similarly in [4]. The error is no more than 10%. The main source of errors is the measurement of the current of primary electrons and delta electrons, accuracy of the thin foil thickness determination. This dependence makes it possible, regardless of the change in the thickness, material of the target, and the energy of the primary electron beam, to estimate the delta electron yield in the case when a thin amorphous target is used or single crystal foils without including orientation effects.

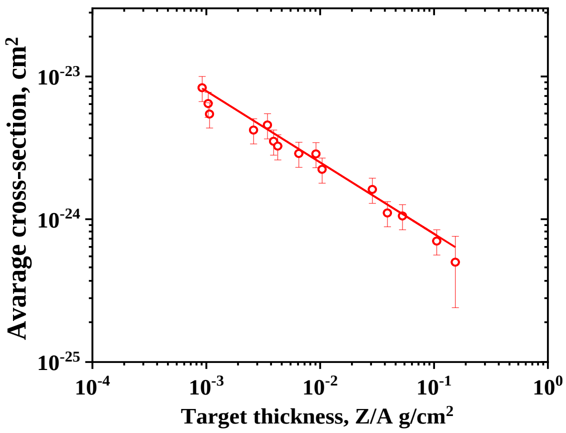

Fig. 4. The average cross section of the generation and emission of delta electrons from foil as a function of the electron target density (X and Y axis have Log scale). The points are the experimental data from the Table; the line is the fitting results by the function $\sigma = 2.5 \cdot 10^{-25} \cdot t^{-0.5}$

Knowledge of the cross section is also important in the design of secondary emission monitors, where foil thickness and target material play an important role in their functional design. In the case of application of a monitor which consists of several thin films, it is possible to obtain optimal conditions for signal amplification without primary charge particle beam losses. This approach is applicable for high energy charge particle beam measurement technique.

A special case is, of course, the study of the delta electron yield from single-crystal structures, namely the influence of the channeling effect, which was partially investigated earlier [6, 7].

With a more accurate determination of the values of the delta electron formation cross sections, the techniques are available for studying the degree of crystallization of thin foil, as well as the content of impurities, since the delta electron yield depends on both the orientation and the chemical composition of the target material.

The application of the proposed universal curve makes it possible to determine the optimal values of the thicknesses of experimental thin foils, when the of delta electron yield is sufficient for registration and their absorption is insignificant.

CONCLUSIONS

The results were obtained from the generalization of the delta electron yields on the basis of experimental data when using electronic accelerators of the NSC KIPT. It is shown that the delta electron yield of practically does not depend on the energy of the primary electron beam, but only on the electron density of the target. It was established that the delta electron yield is proportional to the square root of the target thickness multiplied by the ratio Z/A.

The dependence of the delta electron generation cross section on the electron density of the material was obtained also, which is of important scientific and practical importance. The features application of universal dependence in further studies of the high-energy electron interaction of with amorphous and single-crystal structures [9] and practical applications in the physics of charged particle accelerators [10] are also discussed.

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УЗАГАЛЬНЕННЯ ЕКСПЕРИМЕНТАЛЬНИХ ДАНИХ З ВИХОДУ ДЕЛЬТА-ЕЛЕКТРОНІВ ПРИ ВЗАЄМОДІЇ ВИСОКОЕНЕРГЕТИЧНИХ ЕЛЕКТРОНІВ З АМОРФНИМИ ТА МОНОКРИСТАЛІЧНИМИ МІШЕНЯМИ

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Представлено узагальнені експериментальні результати виходу дельта-електронів, які отримані на прискорювачах електронів ННЦ ХФТІ у діапазоні енергій від 0,5 МеВ до 1,6 ГеВ. В якості експериментальних мішеней використані «тонкі» плівки Be, Al, Si, Ni та Nb. Встановлено, що вихід дельта-електронів пропорційний добутку $\sqrt{T \cdot Z/A}$, де T – товщина зразка в г/см^2, і має лінійну залежність. Показано, що основним фактором зростання виходу дельта-електронів є не енергія первинного пучка, а густина електронів в експериментальній мішені.