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The role of secondary electrons from profile parts of a nanogroove in its SEM image

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Peculiarities of dispersion of secondary electrons in nanogrooves were revealed experimentally as a result of its scanning in a lowvoltage scanning electron microscope. The important role in generation of slow secondary electrons (SSE), forming microscope image, belongs to „external"secondary electrons dispersed by one surface part of a nanogroove to another one. They contribute an additive to signal from scanning point that is due only to SSE emission from it. The phenomenon is most important for nanogrooves with steep edges. The detectable contribution into dispersion of „external"secondary electrons is made by a nanogroove bottom. „External"secondary electrons, dispersed into nanogroove, are able to escape it, to transfer along a sample surface and to induce SSE emission from adjacent parts of a relief structure. This leads to influence of nanogroove edge image from disposition of these parts. 'External' secondary electrons influence the SSE emission from a groove surface modifying property of charge conjugations on this surface.

Keywords: nanometrology, lowenergy SEM, relief structure, surface charge state.

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Introduction

Topographical features of nanocircuits are the main objects of control for industrial scanning-electron microscopes (SEMs). One of the main objectives of control solved with their help is measurement of linear dimensions of nanostructures. Measurements are done by the image of these structures created with the help of low voltage SEMs (LVSEMs). The image is generated by slow secondary electrons (SSEs), emitted from the near surface layer of the object with thickness of several nanometers and therefore capable of showing its nanorelief. SEM image of the nanostructure enables generation of a video signal (VS) curve, i.e. the profile of the SEM detector signal value in the image scanning line. By distance between the selected reference points on the slopes of the VS curve, corresponding to the geometric edges of the nanostructure, its linear size is determined.

Beam electrons penetrate the substrate and initiate secondary electrons (SE) in it, some of which are scattered to the surface and reach the near surface layer (inelastically reflected electrons (IREs)). Interacting with the atoms of this layer, they generate an emission flow of SSEs. IREs are also capable of interaction with charge traps near the surface, changing their state [1]. As a result, the electric charge of the surface section changes, which impacts the emission of SSEs from it. Because of many values of impact it is difficult to estimate SSE emission from a nanogroove, especially from its side walls (SWs). However, it is them who determine the shape of the VS curve slopes, by reference points on which the width is measured.

Some IREs created in the substrate may come out [2] and move to the neighboring sections of the groove surface. They may scatter on them or change their charge state, which complicates SSE emission from the groove surface even further.

It is practically impossible to theoretically describe electron scattering in the groove for the complex profile with changed surface states. Fortunately, today the computer modeling of SE electrons has been implemented using Monte Carlo method. It makes it possible to estimate tracks of motion of sample incident electrons inside and beyond the sample. Movement, scattering and interactions of particles in a solid body are described by probability laws. But the description of scattering of individual electrons takes into account the specific limiting conditions, such as the profile of the groove sections, data on the suggested surface electric charges, conditions of SE exit beyond the surface, on laws of SE interaction with charge traps [1]. Modeling displays the process of subsequent scattering of a particle in a groove as it really happens. Calculations are made for many model electrons incident on the surface, which makes it possible to obtain the model SEM image of the groove and VS curve in the end. However, there is a potential discrepancy between the real and model forms of nanoprofile and the state of its surface charge traps. This causes methodological uncertainty in the values of nanostructure dimensions. Note that the uncertainty of the dimension value for calibration metrological nanostructures must be within a subnanometer range, i.e. depends on the quantity of only a few atom layers [3].

Model estimates of electron scattering are used to confirm the ideas on the process of electron scattering in nanometer grooves. Joint experimental research and model estimates make it possible to identify such features of electron scattering in the nanogrooves that may not be identified by other methods. However, such research is not sufficient, and its results are often not of prognostic, but rather ascertaining or even illustrative nature [3,4].

This paper conducted experimental scanning of nanometer groove samples made at one of the domestic microelectronic enterprises using a state-of-the-art industrial LVSEM. Its objective was to obtain new information on SE scattering pattern in the nanogrooves.

1. Review of literature and objective setting

Recreation of details of the electron scattering pattern in the groove using modeling by Monte Carlo method is presented in [4]. The model structure included several steps in the PMMA (Polymethyl Methacrylate) mask layer with a rectangular profile of 20 nm at step-to-step distance of 40 nm. Estimates made it possible to visualize tracks of individual IREs emitted outside and scattered inside the groove (external IREs (EIREs)), as a result of radiation of its edge by LVSEM electron beam. Most of these tracks start and end in the sections of the profile inside the groove, but some tracks reach beyond. Curvilinearity of these tracks confirms SE motion in the electric field. It is developed by electric charges that arise on the surface of the groove, including on the upper plateau of the step. The authors explain that the charges arose as a result of preliminary model scanning of the step by multiple beam electrons.

In the same modeling of EIRE tracks emitted from the step in the layer of SiO_2 with inclines SWs [2], you can also see that some of them exit the groove and move to the upper base (UB) of the step. The shape of these tracks is also curvilinear. Individual electrons emitted from the groove travelled the distance of up to several dozens of nanometers along the UB surface. The result of EIRE penetration in the SW and UB were the electric charges induced on their surface. The paper [2] (Fig. 10) shows distribution of the induced model potential on the groove SW, which turned out to be asymmetrical due to the beam location at the moment of radiation at the edge of the step. The result of formation of induced charges by a flow of EIREs directed from one of SWs to the neighboring one along with the direction of scanning, differs, in opinion of the authors, from the corresponding one, developed by the opposite flow of EIREs from this neighboring SW to the initial one. Inequality of charges induced on the neighboring SWs of one groove results in various emission of SSEs from them and asymmetry of VS curve peaks. The Monte Carlo method was used to model VS formation from the symmetrical model geometric profile of the groove, and the VS profile curve asymmetry was confirmed. The possibility to form the asymmetric form of the VS curve from the groove with the symmetrical profile was also confirmed experimentally. This confirms their correct explanation of the SW role in formation of the VS curve asymmetry. VS curve asymmetry from the geometrically symmetrical profile may be an important sign confirming the existence of EIRE flows inside the groove.

2. Experiment features

A SW is a section of an inclined plane, which may scatter the incident beam also to the neighboring sections located nearby. Features of the EIRE flow scattering are important, the source of the flow being the beam incident on the groove SWs. We failed to find the description of EIRE scattering features in the conditions close to the ones in our experiments. Literature data was found on electron scattering from flat inclined objects when they were scanned by a beam with higher electron energy [5]. These features may manifest themselves in our conditions as well.

As a result of the inclined incidence of the beam on the plane, the flow of electrons emitted from it is formed, where the electrons underwent inelastic reflection from the surface atom layers of this plane [5]. A part of the scattered flow spreads along the line of geometrical beam reflection from the plane, the other part is scattered diffusely mostly in the direction of reflected beam motion. The angular density of electrons in the diverging EIRE flow is maximum in the direction corresponding to the geometric reflection of the incident beam [5]. The reflected part of the EIRE flow spreads mostly in the incidence plane [5]. The number of scattered electrons with the inclined incidence of the beam on the surface increases with the growth of the incidence angle and may be much higher than the number of the inversely reflected electrons arising at the normal incidence of the beam [5,6].

In contrast to the energy of incident electrons, the electron energy in the scattered EIRE flow varies. It is unevenly distributed in the range of values from the energy of incident electrons to almost zero values [6]. Scattered electrons with the higher angular density have higher energy ([6], Fig. 5). Such EIREs tend to be geometrically reflected from the surface more often when their energy grows, and the incidence angle of the primary beam increases [5] (Fig. 3.35).

EIRE emission ratio B_0 for the smooth surface of silicon at normal beam incidence, as well as relative emission ratio B_θ/B_0 at beam incidence at angle θ to the normal line to the surface was calculated by us in accordance with formula (2) in [6]. Dependence B_0 on electron energy in the beam was presented in Fig. 1, *a*, dependence B_θ/B_0 on θ — in Fig. 1, *b*.

Our groove is scanned by a beam of electrons with energy 0.8 keV, and SW is inclined to its base at angle θ of around 7°. From Fig. 1, *b* you can see that under these conditions the intensity of the reflected EIRE flow is more than 2 times higher than the corresponding intensity at normal incidence and only twice less than the intensity of

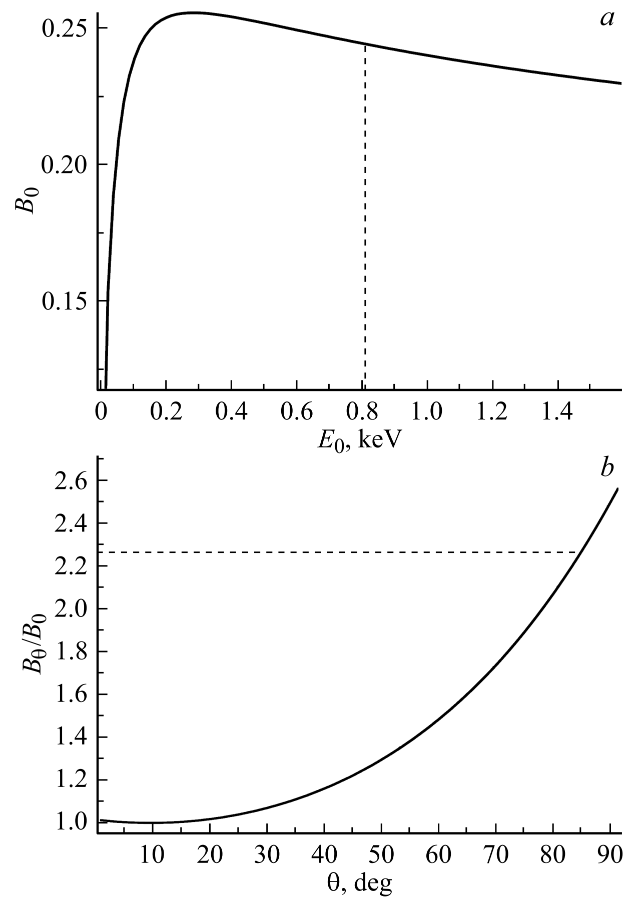

Figure 1. Dependence of emission ratio of inelastically reflected electrons of UB (EIRE) on electron energy in beam at its normal incidence on smooth surface of silicon (a), dependence of relative emission ratio $B_\theta/B_0(\theta)$ at beam incidence on this surface at angle θ (b). Dashed straight lines mean energy of beam electrons (a) and incidence angle 83°, corresponding to inclination of SW (b) towards UB.

the incident beam. Curves are obtained from the equation made on the basis of empirical data. It may be used at electron energy of more than 0.5 keV.

However, at low electron energy and in the sections of the surface with nanometer dimensions the scattering laws may substantially differ from the corresponding laws for the sections of the lengthy, inclined and smooth surfaces upon incidence of the beam with high energy of electrons upon them. It is expected that under the conditions of our experiments, the share of diffuse scattering will increase, and the share of conventionally reflected SEs will decrease.

Confirmation of the possibility of IRE flow scattering by inclined SWs (similarly to their scattering from the inclined surface) at low energy of the incident beam we could see in the results of the model experiment in [7] (Fig. 26). There the SSE emission was estimated from a trapezoidal step in silicon (using Monte Carlo method), on which the beam fell with diameter of 5 nm. The step height varied from 50 to 200 nm at invariable base of SW with size of ~ 9 nm (with variation of the SW inclination angle from 10 to 2.5°). At low height of the step the VS curve at the section of the lower plateau (LP) near the SW base is a narrow minimum in the form of a „spike“ [7] (Fig. 26). As the step height increases, the spike gradually expands, spreading to the distance of more than 30 nm, which greatly exceeds the dimeter of the scanning beam. We suggested that spike formation was explained by reflection of the EIRE flow from the lower section of the SW that changes the SSE emission near the SW base. Having reflected from the upper sections of the SW, this flow expands and diverges to a larger distance, radiating more of the LP. The spike also expands, reducing the SSE emission in the entire length of the LP. In this case appearance of the spikes on the VS curve could be treated as a sign of EIRE existence inside the groove (similarly to the asymmetry of the VS curve).

Another sign of the reflective scattering of the beam inside the groove and formation of the EIRE flow may be the confirmation of its impact on the emission from the adjacent sections of the groove surface. Because of the potentially inclined incidence of EIRE flows on the adjacent sections, their scattering may be happening many time, and intensity of these flows must be higher then upon normal incidence of electrons upon them. Since the SSE emission from the scanned and adjacent sections will be recorded by the SSE detector in a joint manner, the VS for the point scanned at this moment of time will be larger. Therefore, the shape of the VS curve must depend on whether the step is single (where there are no multiple EIRE reflections) or group.

Differences of the conditions in our experiments from the ones in other papers are related to how the surface charges are induced. The review of literature contains evidence of charges inducted on the surface of sections in relief structures formed in dielectric materials. Our structures are formed in silicon and are only coated with a thin layer of natural oxide. The important issue is the issue on the possibility of induction and long-term existence of the charges in this layer and their impact on the SSE emission from the surface sections of the relief structure. Experimental confirmation of such possibility is provided in [8]. Long-term scanning of relief structures in LVSEM caused monotonous change of the VS curve shape (and accordingly to gradual change in the step dimensions). After scanning is stopped, and the samples have been kept in air, the dimensions of steps were partially restored at the initial values. It was presumed that induced charges exist and are found in the natural oxide layer on the silicon surface.

The opposite conclusion was made in [8], even though the relief structures and conditions of their scanning practically match ours. This paper compared the results of such structures scanning before and after etching of the natural oxide, and change of the SSE emission was estimated on their silicon surface, where the oxide film is gradually growing. In our opinion, the conclusion on absence of induced charges in the natural oxide on the surface of the relief structures in silicon is the result of wrong interpretation of some obtained results.

At low energy of incident electrons in our experiments the influence of near surface layers of the sample on the scattered SE flow should potentially increase. If a beam of electrons with energy 0.8 keV affects the substrate, they may penetrate the depth only for ~ 20 nm at their normal incidence [9]. In this near surface area two charge layers will be formed. Near the limit depth, a negative charge layer will be located [10]. If the average energy of EIRE flow is ~ 0.4 keV, the depth of their penetration into silicon at normal incidence of the beam on the surface must reduce to 5 nm [9]. Because of the inclined incidence of this flow, the depth will only make several units of a nanometer. Near the surface itself a positive charge layer will be formed. At such small depths of electron penetration in the substrate the lamellar charge structure may partially be imposed upon a heterogeneous physical structure, since the surface is coated with a layer of natural oxide with thickness of 1.5–2 nm. Positive charges may form and be maintained long-term in the traps of this layer, being capable of long-term impact at SSE emission [11]. The impact may be implemented via change in the work function for the emitted SSEs [5]. The thickness of the oxide layer, the density of charge traps in it and conditions of radiaition at different parts of the relief structure profile are different. As a result the emission properties of these sections should also differ.

3. Experiment

Taking into account the literature data, we suggested that the most important sign of existence of EIRE flows scattered inside the groove is VS curve asymmetry. It was necessary to reliably fix the minimum deviations from the symmetrical shape of the curve. To obtain SEM images, we used an industrial LVSEM at beam energy of 0.8 keV and current of 8 pA. A scan (an image of a step, which was used to form the VS curves) was created by averaging the images of 32 frames as a result of subsequent scanning of the same surface section. The VS curve was formed from the scanning lines of the same scan. The VS value in each point of the curve was obtained as a result of averaging the signal values in the corresponding points of all scan lines. To exclude the high frequency noise on the VS curve, the amplitude in its every point was determined by averaging VS values in several neighboring points („by a travelling" digital filter). This had to eliminate the impact of non-repeatability of scanning conditions at the shape of curves and the position of reference points on them.

The objects of research were grooves with inclined SWs. They were formed on a silicon plate by plasma-enhanced chemical etching. Some steps were arranged as single, some — within a periodic lattice (group steps). Step profile had a complex shape. On a relatively wide „pedestal" a narrow trapezoidal elevation was arranged with a flat UB (see the groove profile between steps in Fig. 2). The width

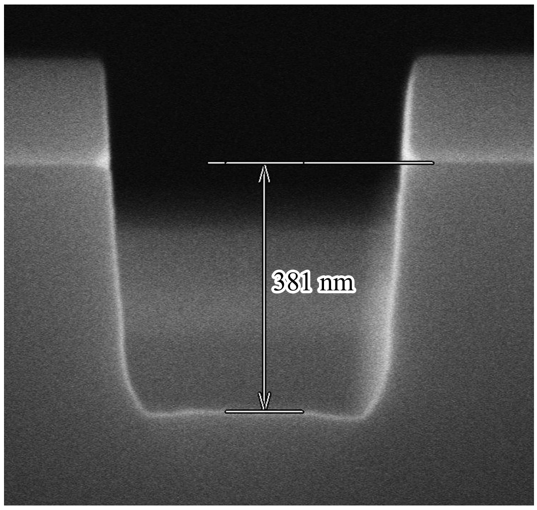

Figure 2. Groove profile between two group steps in nanocircuit.

of the flat UB section of the steps was around 300 nm, of the lower plateau (LP) - ~ 200 nm, the width of the entire SW projection ~ 50 nm. With the full depth of the groove ~ 355 nm the SW inclination angle to the LP for the trapezoidal section of the upper part of the SW made $\sim 7°$. The surface of all steps and grooves is coated with a layer of natural silicon oxide.

According to our estimate, the size of the beam incident on the SW was slightly less than the SW projection on the sample surface. If the reflected — scattered flow of EIREs exists, it should at some moments radiate the sections of the groove bottom near the SW. And when these sections of the bottom are scanned, the lateral tabs of the EIRE flow emitted from them should radiate the SW sections adjacent to the bottom. Therefore, the sections of the groove profile adjacent to its corners should differ by SSE emission level from the sections that are distant from the corners. The bottom section width near the SW with the changed SSE emission level from it owing to „backlight" with EIRE flow should make, according to our estimate, 20–30 nm.

It is important to experimentally assess the involvement of the depth sections of the grooves in formation of lower sections of the VS curve, and in formation of the curve asymmetry. For this purpose we supplied a positive potential to the special „booster" electrode. This made it possible to pull the SSEs emitted from the side surfaces and from the bottom of narrow grooves, to the detector.

4. Results and comments thereto

The source of asymmetry in [2] is the scanning direction of mirror symmetrical ones in the SW profile. Therefore, we tried to detect it, having compared the VS curves for group and single steps with no adjacent SW. Another method of detection — change of scanning direction for group steps (right to left) with expected mirror change of the asymmetry shape. Fig. 3, *a* presents VS curves obtained by scanning of the group step by a beam in two opposite directions. Fig. 4 — same, but for a single step. In both versions the scanning was carried out with booster off. For curves scanned in the reverse direction, the measurement of point coordinates is performed from right to left. But for VS display, from left to right. If there is asymmetry because of scanning direction, the shape of the curves obtained as a result of straight and reverse scans, must be the same when imposed on the same field.

VS curve asymmetry is visible in Fig. 3, too. It manifests itself not only in the height and shape of the peaks, but in the VS values on the left and right sections of the curve, corresponding to the LP of the groove sections (see curve *1* in Fig. 3, *b* relative to the horizontal straight line). Note that asymmetry of the peak height in the curve *1* in Fig. 3, *b* is partially caused by asymmetry of LP sections to the right and to the left from these peaks. As you can see in Fig. 3, *a*, the shape of the peak asymmetry changed in mirror-like manner as the scanning direction changed. The same appearance of asymmetry in peaks in Fig. 3, *b* (after the computer change of scanning direction from the reverse one to the straight one) additionally confirms absence of asymmetry dependence on the scanning direction. This conclusion is confirmed by the results of single step scanning shown in Fig. 4. As you can see, the curve asymmetry in Fig. 4 is even more visible than in Fig. 3. Besides, peak height asymmetry is almost fully explained by the asymmetry of VS values on the lower plateau of the structure.

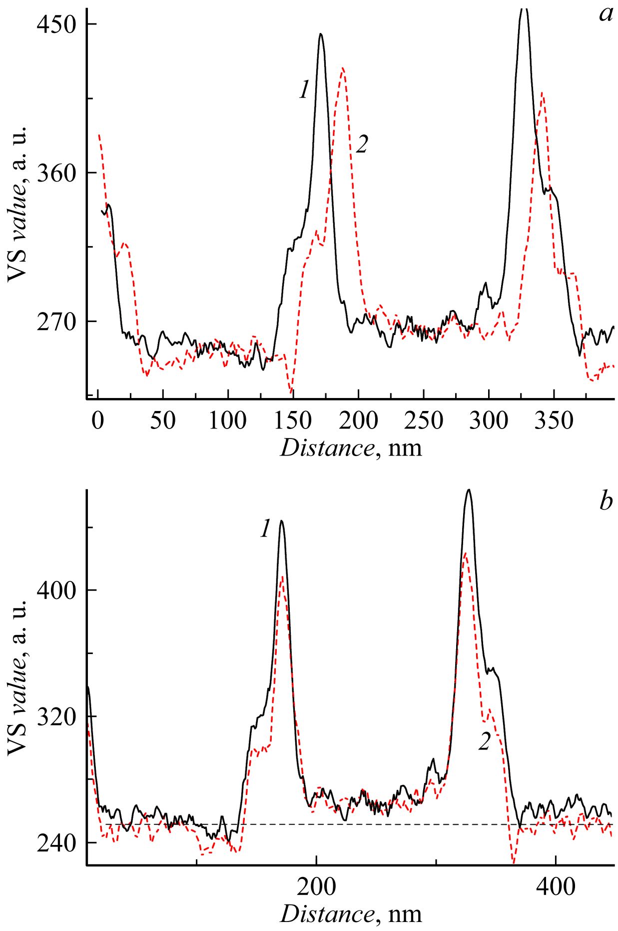

Figure 3. VS curves in fragments (a, b) are obtained from one fragment of the group step as a result of straight *1* and reverse *2* scans with booster off. *b* — curve *1* — repetition *1* from (f), curve *2* — mirror-like scanned curve *2* from (f), imposed on the curve *1*. The dashed horizontal line visually underlines the asymmetry of VS curve in the sections of the lower plateaus near the step (b).

An important part of the obtained VS curves are minimum spikes from the outer side of the peaks. This part of the curve shape is especially visible when beam electron energy is less than 1 keV for single steps [7]. And in our case the spikes are more visible on the curves obtained when single steps are scanned (with booster off). The spike width is around 50 nm. Signal asymmetry in the spikes is related to asymmetry of signals on the corresponding sections of the LP.

Involvement of the depth sections of grooves in the formation of curve asymmetry was tested by us via application of positive potential on a „booster“ electrode. Fig. 5 shows VS curves from steps on the plate obtained as a result of their scanning in the mode without a booster and when it is on. As you can see, the degree of asymmetry of VS curve peaks with the booster on does not change substantially, however, the levels of VS change in the sections of the curve corresponding to the UB and LP. In particular, when the booster is switched on, spikes disappear in the curve corresponding to a single step.

We tried to detect EIRE flows inside the groove by comparison of VS curves from group and single steps. Above it was presumed that addition of the SW to a single step (SW of the neighboring group step) may change these flows, which may affect the shape of the VS curves. Typical results of the experiment are presented in Fig. 5.

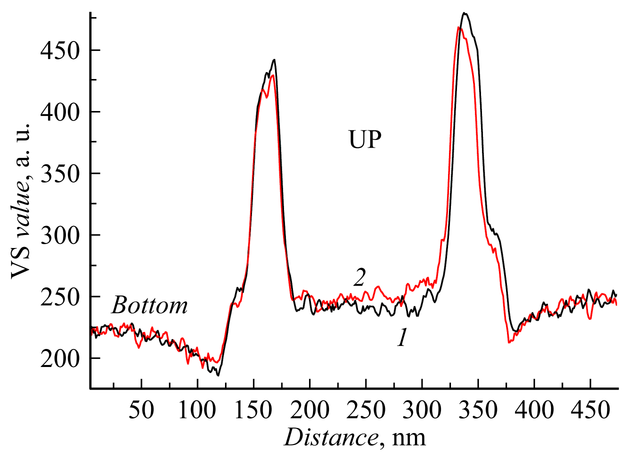

Figure 4. VS curves obtained by scanning of a single step with booster off: *1* — in straight, *2* — in reverse directions. *Bottom* corresponds to the groove bottom, *UP* (*upper plateau*) — to the upper base.

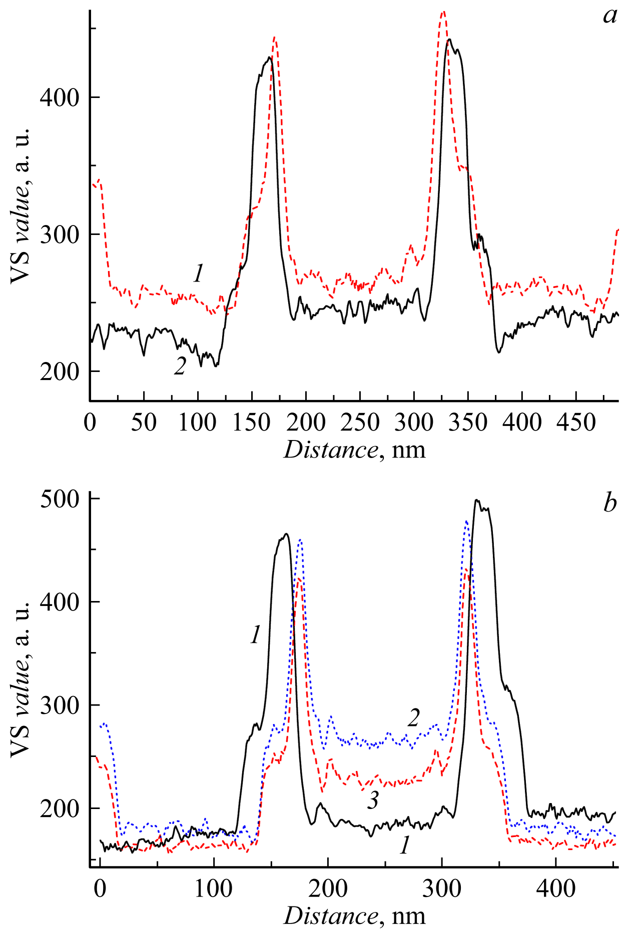

Figure 5. VS curves obtained by scanning of single and group steps with booster off and on: *a* — in the mode without a booster (*1* — for a single step, *2* — for a group one); *b* — scanning with a booster (*1* — for a single step, *2* — for a group one, *3* — same but for scans along SW).

As you can see, the VS value in the section of the profile corresponding to the bottom of the groove in all scanning modes for a group step is higher than for a single one. The VS value also increased in the curve sections corresponding to the step UB. Note that the increase of the VS value for the UB area is lower than for the LP section with the booster off (Fig. 5, *a*, curves *1* and *2*). But when the booster is on, the situation changes noticeably: VS increase on the UB for a group step becomes several times higher than for a single one (curves *1* and *2* in Fig. 5, *b*). It seems that the UB of the group step „senses" the neighbor's presence.

5. Results and discussion

5.1. Features of EIRE scattering in groove

We concluded on existence of the EIRE flows inside the groove by variations of the shape of VS curves, which arise as a result of changes to the experiment conditions. From Fig. 5, *a* you can see that the placement of the SW from

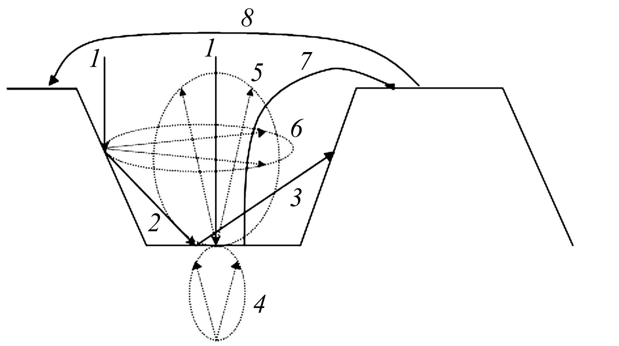

Figure 6. Circuit diagram of electron flows in groove. *1* — incident beam, *2* — EIRE reflected and scanned from SW, *3* — secondary EIRE reflected and scanned from bottom, *4* — IRE from substrate, *5* — EIRE scattered from bottom, *6* — EIRE scattered from SW, *7* — EIRE flow from scanned LP to UB of step, *8* — EIRE flow from scanned UB to neighboring UB.

the neighboring step of the group structure next to the single step increased the VS values on the LP and UB. This confirms the fact that the added SW „captures" some IRE flow from the scanned bottom (previously scattered in the vacuum), causing additional emission of SSEs. It is worth noting that as a result of SW addition to a single step, both peaks of the VS curve grow too. This confirms scattering of EIRE flow from the scanned SW of the step to the bottom, and from the bottom — to the added SW. A flow is also possible from the scanned SW directly to the added SW (Fig. 6).

VS increase is also fixed on the UB section with a booster off (Fig. 5, *a*, curves *1* and *2*). It may be explained by an EIRE flow scattered from the scanned UB to UB of the neighboring steps, from which additional SSEs occur (Fig. 6, curve *8*). If the distance between the neighboring steps along the relief surface exceeds 400 nm, such explanation requires additional confirmations. It is difficult to explain by this method the drastic increase of SSE emission from the UB as a result of SW addition with the booster on (curves *1* and *2* in Fig. 5, *b* for a single and a group steps, accordingly). In this case the EIREs scattered from the scanned UB must be removed from the neighboring UBs by the booster field. It may be suggested that drastic VS increase on the UB is caused by the EIRE flow developed inside the groove, but withdrawn from it only by booster potential. Further this EIRE flow is partially transferred to the UB to be scanned (Fig. 6, curve *7*). However, transfer of EIREs withdrawn from the groove to the UB and scanning of this UB happen at different moments of time, therefore, the transfer of EIREs from the groove may be only the condition for increasing the SSE emission from the UB.

We suggested that increase of the SSE emission from the UB is implemented by a two-stage process. At the first stage EIREs born inside the groove at the previous moment of time move under effect of the booster on the UB subject to scanning. EIREs deposited on it vary the state of its charge traps, which causes reduction of the work function for the SSEs on the UB surface. When it is scanned by the beam, at the next moment of time the SSE emission from the UB increases.

Note that the appearance of the pulling field in the groove will not increase, but will rather decrease the SSE emission from its bottom (VS value in Fig. 5, *a* without a booster ∼ 250 a.u., with a booster in Fig. 5, *b* — less than 200 a.u.), but at the same time it increases the height of peaks. It may be presumed that IREs emitted from the groove bottom form the SSE flow from the sections of the bottom and the SW, weakly impacting the EIRE flow from the upper sections of the relief structure. Addition of the booster redirects these EIREs to the upper part of the groove.

The hypothesis on SSE generation in process of the two-stage radiation of the relief structure sections is confirmed in the unusual mode of its scanning. In this mode the groove is scanned by movement of the beam along the SW, and not across it, as usual. Note that the middles of the adjacent sections of the groove profile are separated with a distance of ∼ 150 nm (at beam diameter of less than 15 nm). In case of transverse scanning, the EIRE flow scattered by the first SW along with scanning radiates the adjacent sections of the groove along the scanning line, which will further be scanned by the beam after approximately a dozen of microseconds. In case of „longitudinal" scans the beam electrons will scan the adjacent sections of the groove after their radiation with EIRE flow in a time interval which is approximately several hundred times longer. Obviously, different time intervals between the scattered flow of EIREs from the neighboring section and the incident beam radiating one section of the groove profile, cause different emission of SSEs from them. The result of impact of various scanning conditions at the VS curve is shown for the group step with the booster in Fig. 5, *b* (curve *3* for the longitudinal scan and curve *2* for the transverse one). You can see that during longitudinal scanning the VS value from the groove bottom is the lowest, and the VS value from the UB decreases as well, including the height of the peaks in the SW sections (compared to the option of the transverse scanning of dashes).

The results of this experiment made it possible to presume additional details of the two-stage process for SSE emission formation. Previously the hypothesis was presented that the EIREs scattered from the groove sections during its transverse scanning move to the UB of the nearest step and sensibilize the charge centers there. We suggest that the EIREs scattered by the SW to the LP of the groove also sensibilize the charge centers, but on its bottom. Sensibilization stays for the time of more than a dozen microseconds, which is enough to move the beam from the SW to the groove bottom. As a result, when the bottom is scanned with the incident beam, the increased SSE emission occurs. But in case of longitudinal scanning of the groove, the beam moves from the SW to the bottom with a time delay of several milliseconds. Because of this

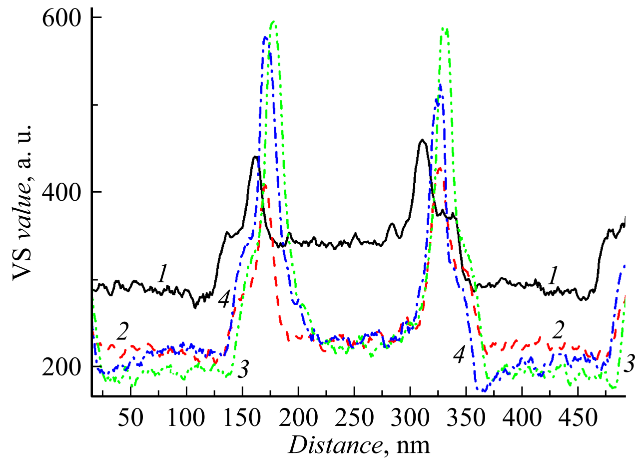

Figure 7. VS curves obtained at different beam energy: *1–3* at 0.3, 0.8 and 1.6 keV accordingly (without a booster), *4* — at 1.6 keV and with a booster.

the sensibilized charge centers on the bottom have time to return to the initial state, as a result of which the SSE emission from LP acquires the value comparable to the emission from a single step (curves *1* and *3* in UB (UB-upper base) and LP (bottom) sections in Fig. 5, *b*). As you can see, in case of longitudinal scanning the SSE emission from the UB also increases vs the emission from a single step, but much less when compared to the transverse scanning (curves *3* and *1* in UB section in Fig. 5, *b*). This means that the sensibilized state of the charge centers on the surface of the groove sections owing to their pre-radiation should continue from dozens of microseconds to units of milliseconds.

The features of the two-stage process raise an important question: why the EIRE flow and the scanning beam, which together cause SSE emission increase, affect the silicon surface differently. We related the difference in the effect of these groups of electrons to their energy. In [1] the results are presented from the experiment of relief structure image formation on a silicon substrate when it is scanned by electron beams with different energy. It turned out that when the beam electron energy increases from 0.3 to 2 keV, the SSE emission from the same sections visibly decreases. Such dependence between these values was confirmed by us when we scanned our grooves. Fig. 7 shows VS curves obtained at different values of the energy of the beam incident on the groove surface. You can see that the VS from the LP of the groove decreases as the electron energy increases in the beam.

Since EIREs are born with energies in a wide spectrum of values [5], those should also appear, the energy of which is less than that in the electrons of the beam. Falling on the bottom of the groove, they may modify the state of the charge centers, which are located, probably, near the actual surface of the silicon oxide layer. At the stage of the bottom scanning by the beam, its electrons skip these centers, not changing their state. But for the SSEs generated by IREs from the substrate depth, the work function decreases.

The situation changes in case of longitudinal scanning. Scattered EIREs radiate the LP before arrival of the incident beam there several milliseconds earlier. Since the charge centers maintain their modified state for a shorter period of time, in a specified interval of time the beam electrons with higher energy „pierce“ the layer of these charge centers, not varying their state. A flow of emitted SSEs created by inversely scattered IREs from the substrate is no longer capable of overcoming the potential barrier developed by the charge centers, which returned to their initial state. As a result the emission of such SSEs reduces.

5.2. VS curve asymmetry

The source of peak asymmetry in the VS curves is, presumably, non-orthogonality of the LVSEM beam to the scanned surface. Indeed, it turned out that the appearance and the degree of peak asymmetry do not reflect the possible geometric difference of neighboring SWs even from a quality point of view. Indeed, from curves *1* and *2* in Fig. 7 (obtained at 0.3 and 0.8 keV, accordingly) one may see that the left peaks are smaller than the right ones, and for curves *3* and *4*, obtained at beam energy 1.6 keV, — the right peaks are smaller than the left ones. For curves *3* and *4*, obtained at various states of the booster, the degree of asymmetry also differs. Therefore, asymmetry of curve peaks substantially depends on the scanning conditions and on the fact whether the steps are single or group. Another important observation — asymmetry in curve peaks to a large extent (and for a single step almost fully) depends on the asymmetry of VS values on LP (Fig. 4). VS asymmetry on these sections of curves occurs, presumably, because of different scattering of EIREs from asymmetrical SWs. A steeper SW (with a large angle of incidence of the beam on it) generates a scattered EIRE flow directed to the SW base, besides, with a somewhat higher energy than a similar flow from the neighboring SW (as in [6]). Such flows generate minimum spikes on the VS curve on the outer side from its peaks. A less steeper SW generates a spike that is not as deep (Fig. 4), scattering the EIREs with somewhat lower energy and thus causing a higher SSE emission. This causes asymmetry of VS values on curve sections corresponding to the left and right LP, contributing to the corresponding asymmetry of the curve peaks. The highest extent of VS curve asymmetry is found in the LP sections for a single step with a booster off (Fig. 4, 5, *a*). The lowest degree of asymmetry is recorded for group steps on curves *2, 3* (Fig. 5, *b*).

We explained it as follows. As a result of scanning the groove LP surface shall also be charged positively as the UB ([2] Fig. 10). For this reason some emitted flow of IREs will be scattered along its surface. Particles of this flow chaotically moved along the surface in different directions are distributed evenly in all sections of the bottom. As a result of IRE interaction with the surface traps, the potentially uneven distribution of charges takes place on the LP near the SW base under exposure to the flows of EIREs from the SW. Apart from balancing of the charge density in the lengthy LP sections, spikes disappear in the VS curve (curves *1* in Fig. 5, *a* and all the rest in Fig. 5, *a, b*).

5.3. Discussion results

Signs were found that the laws of beam scattering by the inclined plane (for electrons with high energy) were reproduced for an object in the form of a side wall (SW) of a groove in silicon under incidence of a beam on it with electron energy 0.8 keV. The experiment comparing VS from a single and group steps (upon „addition“ of SW from the group step to the single one) confirms „reflection“ of some „external“ inversely reflected electrons scattered inside the groove (EIREs) from one sections of the groove to the other ones. Multiple scattering of EIREs inside the groove is possible, when the important role belongs to its bottom. Each of the groove sections radiated by EIREs contributes to formation of all sections of the VS curve (including change of the VS value on the step UB). Owing to „reflection“ of EIREs from the SW, uneven radiation of the groove bottom appears, which causes uneven emission of SSEs from it. This assumption explains formation of minimum spikes on the VS curve on the outer sides from its peaks.

An especially noticeable phenomenon was increase of SSE emission from the UB found by comparison of VS curves from single and group steps. It is probably happening because of EIREs transfer from the radiated UB section to the neighboring ones along the sample surface. The possibility of such transfer was found by modeling EIRE scattering by the Monte Carlo method in [2]. The found phenomenon is especially noticeable with the booster on. In this case the „bottom“ EIREs that arose inside the groove travel towards the exit from its aperture. Some of them probably get on the UB of the neighboring step, which causes change of the SSE emission from it. However, „bottom“ EIREs are developed by the beam prior to UB scanning, therefore, they cannot do it directly.

We suggested that the growth of SSE emission from the UB was caused by a two-stage process, where surface charges play a critical role. At the first stage some „bottom“ EIREs sensibilize the charge traps on the surface of the nearest UB. Upon its subsequent scanning, the IREs emitted from the UB surface, cause emission of SSEs which exit the sensibilized surface. The suggestion on the two-stage implementation of the process of SSE emission increase from the UB is confirmed by the comparison of groove scanning results in the longitudinal and transverse directions. In process of longitudinal scanning, the neighboring sections of the relief are scanned not in the process of single expansion of the incident beam, but after some time. It seems this results in disappearance of the discussed increase of the emission from the UB.

Since the charge traps on the adjacent section of the groove are located in the thin layer of oxide film, they may vary their state only at certain energy of electrons incident on them. For this reason the incident beam with electron energy that is not compliant with the level of trap energy, is not able to modify their state. However, the EIRE energy may vary in the wide range of values, as it happens for the EIREs scattered by the inclined plane in [5]. Therefore, the EIRE flow should also include, among other things, electrons with relatively low energy, capable of changing the state of the traps on the surface of the UB or LP. The possibility to increase the SSE emission from the surface radiated by the beam with low energy of electrons, is confirmed by the result of our experiment (Fig. 7), and also literature data.

The discussed increase of the SSE emission from the relief sections, which are exposed to beam scanning at the next moment of time, may be explained as follows. At the previous stage an EIRE flow is formed from the relief sections radiated by the beam, to radiate the section to be scanned at the next moment of time. This flow with a relatively low energy of electrons sensibilizes the adjacent section of the groove or the neighboring surface of the relief beyond it for a short period of time. The incident beam following the EIRE flow causes a flow of IREs from the silicon substrate. It emits SSEs with reduced work function from the surface.

Conclusion

It was confirmed that the critical role in formation of SSEs from the nanogroove surface sections (creating its SEM image) was played by flows of inelastically reflected secondary electrons scattered inside the nanogroove — EIREs. They are born by an incident beam with electron energy 0.8 keV and are scattered by side walls not only (as it was presumed) diffusely, but also in a reflected manner. The reflective scattering may be multiple, the main contribution thereto is made by the groove bottom. EIREs flows scattered to the neighboring sections of the groove, generate additional SSEs that are summed up with the SSE flow from the scanned point. This changes the VS from the scanned point and changes the SEM image of the groove that would be produced in the absence of the EIREs.

The results of the model estimates were confirmed on the EIRE ability to go beyond the limits of the groove and be scattered along the sample surface for the distance exceeding the groove size. This makes it possible to explain the experimentally fixed impact of the scanned section of the relief profile at the SSE emission from the next section along with the scanning.

The role of the groove section surface is not reduced to formation of EIRE flows only (as presented in [8]). It is confirmed that EIREs impact the state to the surface in the neighboring sections. Probably, they modify the charge traps on their surface for the time comparable to the time of image line expansion.

For a wide groove with small depth and low-sloped SWs the impact of the EIRE flows to the shape of the VS curve must be decreasing. In this case the formation of the SEM image may occur preferably by generation of emitted SSEs created by the IRE flow from the substrate without their scattering in the groove. Such concept of SSE generation was the basis for the method of nanostructure size measurement in [12]. Such representations make it possible to justify the methodological simplification of the shape of edge sections in the VS curves with exclusion of peaks and spikes from them. VS curves with the simplified shape are used further to define the linear dimensions of nanostructures on their basis. However, the reference points corresponding to the boundaries of the profile areas, whose position must be specified as accurately as possible, are located exactly on these edge sections.

The paper results may help to improve the idea on the scattering of secondary electrons in nanosize grooves. On the practical level they will make it possible to create an improved method for linear measurements of nanostructures using a VS curve, which will enable more accurate display of the position of geometric boundaries of these nanostructures on it.

Conflict of interest

The authors declare that they have no conflict of interest.

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