Electron emission from ion-bombarded SiO_2 thin films

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The electron yield from SiO_2 films on Si was measured as a function of oxide thickness and ion energy for 150–300 keV H^+, He^+, N^+, Ne^+, Ar^+, Kr^+, and Xe^+ ions. For oxide films thicker than 200 Å, the electron yield was found to be approximately independent of oxide thickness. The electron yield from the thick oxide increased as a function of the energy deposited D in electronic excitations with approximately the form $D^{0.65}$ and not D as expected from theory. Close to the SiO_2/Si interface, unexpected variations in the electron yield with oxide thickness, dependent on ion mass and energy, were found. Experiments were performed to investigate whether or not the oxide surface was charged by the ion beam, but such effects could not be observed. However, a satisfactory interpretation of the data could be obtained with a model previously suggested for explaining the dependence of the electron yield on the angle of ion incidence. In this model, the positive charge left behind in the oxide by the liberated electrons within the electron cascades of individual ions, causes the probability of escape of electrons to decrease with increasing electron yield.

I. INTRODUCTION

The phenomenon of electron emission from matter induced by energetic particles is well known and is of great importance in many applications, for example, in measurement of ion currents,[1] in plasma-wall interactions,[2,3] and in surface analysis techniques such as ion microscopies and scanning electron microscopy. Often, the energetic particles impinge on a substrate with a thin overlayer, for example an oxide. For a thick overlayer, the electron emission will be determined by the overlayer material only, but with decreasing oxide thickness a gradual changeover to the substrate electron emission is generally anticipated.

Theoretically, the electron emission induced by electrons and ions has been rather extensively investigated.[4–8] Recent theories predict a linear dependence of the electron yield on the energy deposited by the projectile to excitations of electrons in the target surface, D; that is,

$$\gamma = \Lambda D \ , \tag{1}$$

where γ is the electron yield (electrons/ion), and Λ is a parameter that depends on the target material only.[7] For ion bombardment the contribution to D from recoiling target atoms can be taken into account by splitting D into two parts:[8]

$$D = D_p + D_r = \beta S_e + D_r \ , \tag{2}$$

where D_p is the energy deposited directly by the projectile to the target electrons, D_r is the recoil contribution, S_e is the electronic stopping power of the ion, and β is a factor which takes into account the transport of energy by the target electrons. In other theoretical approaches, the unique interaction in each specific ion-target combination is emphasized, and a general scaling law as in Eq. (1) is disputed.[9]

Experimentally, Eq. (1) has been roughly confirmed for ion bombardment of metals and semiconductors. For proton bombardment, the agreement between Eq. (1) and experiment is generally quite good, whereas for heavy ion bombardment (> 100 keV) for some materials the electron yield is found to increase more slowly with D than predicted by Eq. (1).[10–13]

The electron emission from insulators has been investigated,[14–16] but it is by far not so well documented as that of metals. Generally, the electron yield has been found to be much larger for insulators than for metals and semiconductors.[11,17] This has been attributed to a larger escape depth, which is due to a larger inelastic mean free path, and to a lower surface barrier for excited electrons in insulators than in semiconductors and metals.[14,15,17] The dependence of the electron yield on D has not been thoroughly investigated for insulators.

In a previous study, it was shown that the electron yield from SiO_2 increases approximately as $D^{0.73}$ when the angle of ion incidence is varied.[18] It was suggested that the probability of escape of electrons decrease with increasing electron emission, since the number of attracting holes left behind by emitted electrons increase with the number of electrons escaping. To evaluate if a similar effect could also be observed for varying ion mass and ion energy, an investigation of the electron emission for a thick SiO_2 film, was performed. Furthermore, the electron yield has been studied as a function of SiO_2 film thickness to investigate the SiO_2-to-Si transition in the electron yield.

II. EXPERIMENTAL PROCEDURE

The electron yield was measured on SiO_2 films thermally grown in dry oxygen at 1100 °C on Si(100) n-type 40–60-Ω cm substrates. The initial oxide film thickness varied from 650 to 98 Å, as measured by ellipsometry before mounting in the chamber. Experiments were performed in an ion-pumped UHV chamber[19] with a base

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pressure of 2×10^{-9} mbar, connected to the Chalmers 400-kV ion accelerator. Before mounting in the chamber, the samples were immersed in an ultrasonic bath for 3 min in acetone, followed by 10 min in distilled water.

During sputtering, the ion beam was defined by a 3.5-mm-diameter aperture, whereas when the electron yield was measured the ion beam was defined by a 1-mm-diameter aperture. γ was determined by measuring the total current (ions plus electrons) to the target, which was biased at -100 V, and the ion beam current was measured separately in a Faraday cup located between the beam-defining aperture and the target.[10] From these two measurements, the electron yield was calculated.

When absolute values of γ for SiO_2 were to be measured, 15–25 Å of a 650-Å film was sputtered away, and a steady state was reached before γ was ultimately determined. For Xe^+ and Kr^+ ions, a true steady state was never reached since for these ions there was a continuous slight decrease in γ (Fig. 1). A new target position was used for each different ion type, but the same position was used for different energies of the same ion. For H^+ and He^+ ions, which have very low sputtering yields, γ was measured both on new target positions and positions previously sputtered by N^+ ions, but no difference was noticed after an initial rapid transient.

III. RESULTS

Figure 1 shows the variation of the electron yield during sputtering of thin SiO_2 films on Si obtained for 150–300-keV N^+, Ne^+, Ar^+, Kr^+, and Xe^+ ion bombardment. The thickness was obtained by subtracting the ion dose multiplied by the known sputtering rate[20] from the initial oxide thickness, which was 325 or 265 Å. In Fig. 1, unexpected variations in the electron yield with oxide thickness are clearly demonstrated, and these variations are significantly different for different ions and ion energies.

At the beginning of the sputtering, there is a rapid decrease in γ which may be due to contaminant sputtering, which has been found to sometimes lower and sometimes increase γ for insulators.[15] However, it can also be due to the depletion of oxygen in the surface layer, a phenomenon which has been discussed elsewhere,[21] and/or to the introduction of fixed charges in the oxide. After the initial decrease, there is a slow decrease for some ions extending over 20–30 Å, but from this depth to an oxide thickness of about 200 Å, γ is roughly independent of oxide thickness.

For oxide thickness of between 200 and 50 Å, γ for some ions varies rather unexpectedly. In some cases, γ increases before the transition toward the γ of Si, whereas in others there is a monotonous decrease in γ. For Ar^+ ions, the situation changes over from a monotonous to a clearly nonmontonous variation in γ when the ion energy is increased from 150 to 300 keV.

As the oxide is sputtered through, the electron yield gradually converges into the Si value, which is 3–4 times lower than that of SiO_2, in qualitative agreement with predictions. The maximum escape depth of low-energy electrons is quite difficult to determine from Fig. 1, because of the varying dependence of γ on oxide thickness, but it could be estimated to be in the region 60–200 Å. This is a large value in comparison with metals, but reasonable in comparison with other insulator escape depths.[22]

One possible complication caused by projectile bombardment of insulators is the charging of the target surface. To evaluate if γ was influenced by charging, the target bias was varied. In Fig. 2, the normalized electron yield $\gamma(V)/\gamma(-90)$ is shown as a function of bias voltage V measured with 200-keV N^+ ions for several oxide thicknesses and for Si. The electron yield is clearly independent of the target bias for voltages below -50 V. Furthermore, within ±3 V, the transition in $\gamma(V)/\gamma(-90)$ is independent of oxide thickness, including 0-Å thickness. This shows that the voltage of the target surface, relative to the substrate, can be assumed to be 0 for all oxide thicknesses. The ±3-V uncertainty is due mainly to the fact that at positive bias voltages a

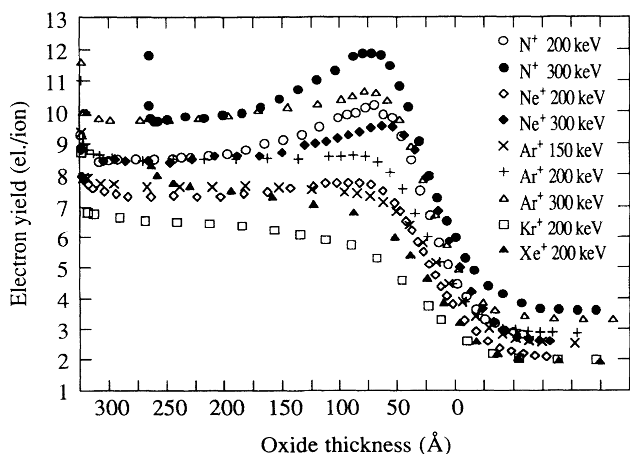

FIG. 1. The electron yield as a function of oxide thickness during sputtering of SiO_2 films, initially 325 or 265 Å thick, on Si substrates.

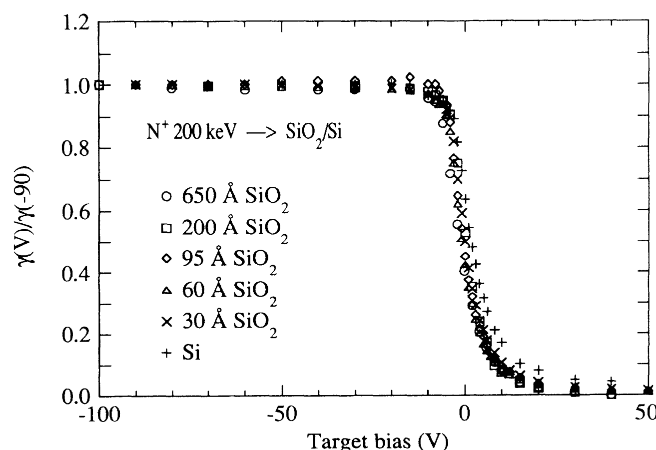

FIG. 2. The electron yield, normalized to the yield at -90-V target bias, as a function of target bias for different SiO_2 thicknesses and for Si.

small number of low-energy electrons in the chamber can reach the target, and the zero current to the target is thus not quite well defined.

Figure 2 also reveals that the energy spectrum of emitted electrons does not change much with oxide thickness. For Si, there is a slightly larger tail toward more positive voltages and thus higher energies of emitted electrons, in qualitative agreement with differences seen in the energy spectra of insulators and metals.[15]

However, even if there is no noticeable macroscopic voltage buildup on the surface, there may be some microscopic charge modification in the oxide due to the emission process, influencing the electron yield. To investigate the existence of such effects, an experiment was performed where the ion current density was varied during the measurements of γ for 200-keV N^+ ions on a 650-Å SiO_2 film. The result, presented in Fig. 3, shows that, within experimental accuracy, there is no variation in the electron yield over five orders of magnitude in ion current density. This indicates that, except possibly for some fixed charges, there is no charge imbalance within the oxide, which is not neutralized before the next ion arrives.

To evaluate the dependence of γ on D, γ for a 650-Å SiO_2 film was measured for seven different ions of 150-, 200-, and 300-keV energy, and the results are summarized in Fig. 4. D was determined from Eq. (2), with S_e taken from tables[23] and D_r from TRIM[24] calculations. A factor similar to β in Eq. (2) is also implicitly included in the determination of D_r, but these factors are expected to be of similar value and are not expected to vary much with ion mass or energy. Therefore, as a first approximation, they were incorporated in the material parameter. It can be seen in Fig. 4 that γ for a 650-Å film is very similar to the γ obtained for films in the region 300–200 Å (Fig. 1). Except for Xe^+, and also to a smaller extent for Kr^+, the data fall remarkably well on a straight line in the logarithmic plot. However, the slope of this line is not 1, as would have been expected from Eq. (1), but 0.62.

An even more pronounced effect can be observed by considering the electron emission data obtained for varying angle of ion incidence,[18] also included in Fig. 4. The

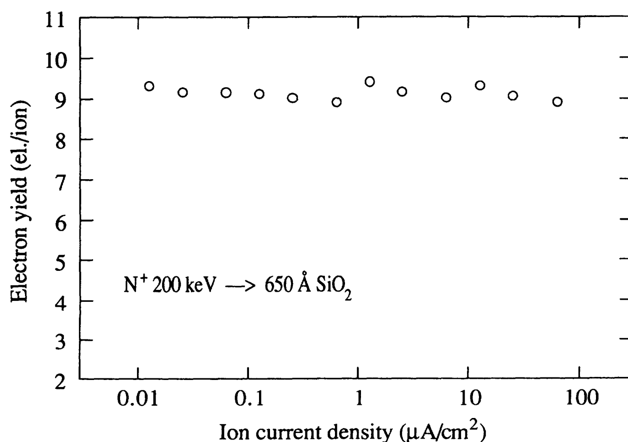

FIG. 3. The electron yield from a 650-Å SiO_2 film bombarded by N^+ 200 keV as a function of ion current density.

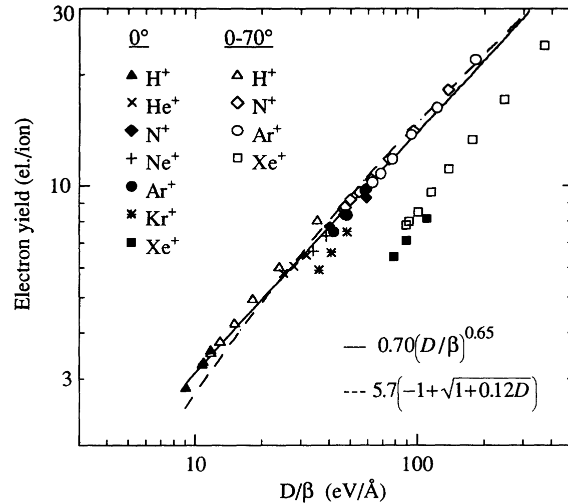

FIG. 4. The electron yield from a 650-Å SiO_2 film for different ions of energy 150–300 keV. Open symbols correspond to data obtained at angles of ion incidence varying between 0° and 70° (Ref. 18), all other data are for normal ion incidence. The solid line is a power fit [Eq. (3)], and the dashed line is the best fit to Eq. (6). The transport of energy by target electrons was not taken into account in the determination of D.

angular variation of D was determined from $\gamma(\theta)/\gamma(0)=D(\theta)/D(0)$ and from measurements of $\gamma(\theta)/\gamma(0)$ for Si, assuming that $D(\theta)/D(0)$ is similar for Si and SiO_2.[18] Obviously, the angular data fit the general trend already established very well. The slope of the least-squares fit (excluding the Xe^+ data) changes very little, from 0.62 to 0.65. Note that even if the Xe^+ data are quite far off the line, the slope of the angular as well as the energy data of Xe^+ are quite similar to the slope of the other data. The slightly higher value of $\gamma(0)$ obtained in the angular Xe^+ measurement is due to a smaller oxide thickness (200 Å) used for the angular measurement.

The results in Fig. 4 thus suggest that the electron yield from SiO_2 is governed by

$$\gamma \approx 0.70 D^{0.65} . \tag{3}$$

Whether or not Eq. (3) is a generally valid expression, the electron yield from SiO_2 increases more slowly with D than linearly, for all conditions represented in Fig. 4.

If Eq. (3) is used to normalize the data in Fig. 1, the result presented in Fig. 5 is obtained. As expected, $\gamma/D^{0.65}$, approximately equals 0.70 $(\text{Å/eV})^{0.65}$, independent of the ion atomic number and energy for oxide thicknesses larger than 200 Å, except for Kr^+ and Xe^+ ions. The variations close to the transition region, however, remain unexplained. Also note that for Si, γ is not well scaled by $D^{-0.65}$ even if D is very similar for Si and SiO_2. In agreement with previous reports,[12,18] the Si γ in Fig. 1 is close to linearly dependent on D, except for Xe^+ ions.

To evaluate if there is a correlation between the nonlinear dependence of γ on D and the unexpected variations in γ close to the SiO_2/Si interface, the two phenom-

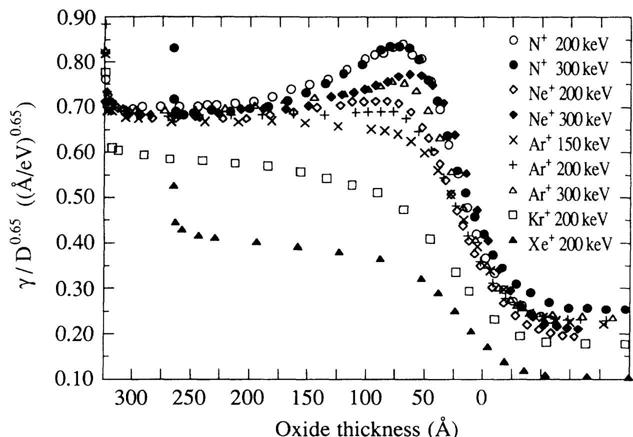

FIG. 5. The same data as in Fig. 1, but with the electron yield scaled according to Eq. (3).

ena were compared. The depth dependence of the electron yield at normal ion incidence, $\gamma(0)$, is thus in Fig. 6 compared with the depth dependence of the normalized electron yield at a 70° ion incidence, $\gamma(70)/\gamma(0)$, for 200-keV N^+ ion bombardment of an initially 211-Å SiO_2 film. $\gamma(70)/\gamma(0)$ is a measure of the nonlinearity in $\gamma(D)$. If γ was linearly dependent on D, $\gamma(\theta)/\gamma(0)$ would be expected to vary as $\cos^{-1}(\theta)$ for 200-keV N^+ ion bombardment,[18] and consequently $\gamma(70)/\gamma(0)$ would equal 2.9. The transition in $\gamma(70)/\gamma(0)$ when the SiO_2 film is sputtered away, seen in Fig. 6, thus reflects the transition from the nonlinear dependence of γ on D for SiO_2 to the linear dependence for Si.

The extension of the transition region is approximately the same for $\gamma(70)/\gamma(0)$ as for $\gamma(0)$, but the increase in $\gamma(0)$, before the decrease starts, does not have an obvious counterpart in the variation of $\gamma(70)/\gamma(0)$. For Xe^+ ions, there is an almost continuous decrease in $\gamma(0)$ with

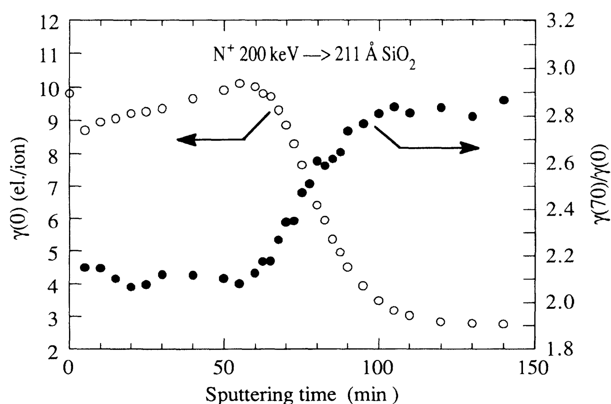

FIG. 6. Comparison of the variation of $\gamma(0)$ and $\gamma(70)/\gamma(0)$ with oxide thickness for N^+ 200-keV bombardment of an initially 211-Å SiO_2 film.

oxide thickness (Fig. 1), whereas the transition in $\gamma(70)/\gamma(0)$ (not shown) is as sharp as that of N^+ ions. Thus, the nonlinearity in $\gamma(D)$ does not seem to be influenced by the variations in γ before the decrease starts, indicating that the two phenomena may have different origins. A further evaluation of the relation between the phenomena is carried out in Sec. IV.

IV. DISCUSSION

A. The nonlinear dependence of γ on D

The applicability of Eq. (1) could be questioned in the case of SiO_2 since the minimum energy required to excite an electron in SiO_2 is about 8 eV, and the condition of cascade multiplication of electrons may not necessarily be fulfilled.[8] However, measurements on insulators show that the energy spectra of emitted electrons are dominated by electrons of energies below 10 eV and have a high-energy tail.[15,25] The condition of cascade multiplication, therefore, seems also to be fulfilled for many insulators at sufficiently high-energy bombardment, and it is reasonable to assume that this is also the case for SiO_2.

The discrepancy of the Xe^+ data with the other data in Fig. 4 is large, but a similar effect has been observed for other materials, including Si (cf. above).[10,11,26] Since the energy and angular dependence of γ for Xe^+ ion bombardment follows the general trend for other ions, it is reasonable to interpret the deviation as due to the absolute value of D not being properly known. This may be due to the fact that the bulk stopping power is not well known, but is could also be due to that the surface stopping power is different from the bulk stopping power.[10,26]

An apparent nonlinear dependence of γ on D is usually assumed to be due to D not being very well known. A number of processes have been proposed which could influence the value of D: (i) Recoil ionization; (ii) the slowing down of the ion;[27] (iii) the surface value of S_e may differ from the tabulated bulk value, for example due to a nonequilibrium charge state of the ion;[10,26] (iv) excitation of the ion;[13] (v) electron cascade anisotropy;[4,28] and (vi) the tabulated bulk values of S_e may not be correct.

In this work (i) is taken into account, (ii) is expected to be negligible except possibly for Xe^+ ions, (iii), (iv) and (v) are anticipated to give deviations from the expected angular dependence opposite to that observed[18] and (vi) is not important to the angular dependence (for $D_r \ll D_p$).

Since none of the above-mentioned processes could satisfactorily explain the nonlinear dependence of γ on D, it is reasonable to assume that it is the fraction of excited electrons being emitted that decreases with increasing D. SiO_2 is an insulator and it is therefore appropriate to search for insulator specific interpretations of the results. The results presented in Fig. 4 are indeed in qualitative agreement with results reported for the electron emission from Al_2O_3 and BeO.[16] In that particular investigation, the results were not evaluated in terms of the electronic energy deposition, but if this is done for the Al_2O_3 results, with recoil ionization roughly taken into account, $\gamma \sim D^{0.70}$ is found to be approximately valid for all ions.

For BeO, the power would be slightly higher, but the thickness of the oxide film was only 50 Å and some influence from the substrate could not be excluded. It should also be noted that because of the low ion energy used in that investigation, D varies strongly within the escape depth of electrons.

An important difference between metals and insulators is that the holes left behind by electrons liberated by an ion beam will be very rapidly refilled by free conduction electrons in metals, whereas in insulators there are, except for the liberated electrons, no free electrons. Thus in insulators there will be a distribution of positive charges left around the ion track which could strongly influence the diffusion and emission of liberated electrons. In SiO_2, the mobility of holes is many orders of magnitude lower than the mobility of electrons,[29] and the holes can therefore be considered as stationary in the time scale relevant for electron emission from a single impinging ion. According to the results presented in Fig. 3, however, the holes are expected to be neutralized before the next ion arrives.

To explain the dependence of the electron yield from SiO_2 on the angle of ion incidence, it has previously been suggested that the probability of escape decreases with increasing electron emission, since the number of attracting holes in the oxide increases with the number of electrons escaping.[18] This could qualitatively explain why the electron yield increases more slowly than linearly with the energy deposited in electronic excitations. To evaluate if this interpretation is also reasonable for the results presented here, the following model was considered.

Most of the holes created in the electron cascades will be neutralized or screened by the released electrons, but some electrons will escape into the vacuum or to other parts of the target. The influence of uncompensated holes on electrons trying to escape from the surface can be viewed as an increase in the surface barrier U (Ref. 6) from U_0 to $U_0+\Delta U$. ΔU will vary strongly in space and time, but it is reasonable to make the simplifying assumption that all electrons are influenced by an average change in U, proportional to the number of uncompensated holes. Furthermore, the number of uncompensated holes in the oxide can be assumed to be proportional to the electron yield and thus on average $\Delta U = c\gamma$, where c is a constant.

The variation of γ with U enters into the material parameter Λ according to

$$\Lambda = b\int_U^\infty \frac{d\varepsilon}{\varepsilon|d\varepsilon/dx|}(1-U/\varepsilon)\ , \tag{4}$$

where b is a constant, ε is the energy above the conduction-band edge of liberated electrons in the oxide, and $|d\varepsilon/dx|$ is the stopping power of electrons in the material.[7] $|d\varepsilon/dx|$ for SiO_2 is not known, but for several metals, calculations have indicated that $|d\varepsilon/dx| \sim \varepsilon^{2.4}$ for energies up to ~ 20 eV above the Fermi energy.[30] However, in contrast to metals, the insulator stopping power for low-energy electrons is expected to be dominated by elastic scattering, and the energy dependence can be quite different. To get a first estimate of $\gamma(U)$, assume that $|d\varepsilon/dx| = a\varepsilon^n$, where a and n are positive constants. Insertion into Eq. (4) leads to

$$\gamma = \frac{kD}{(U_0+\Delta U)^n}\ , \tag{5}$$

where $k=b/a$. It could be noted that, for tungsten, the relative change in the electron yield, $\Delta\gamma/\gamma$, has been found to be proportional to the change in the surface barrier.[31] This observation can be rephrased into Eq. (5) with $n=1$ by an appropriate choice of constants.

By inserting $\Delta U = c\gamma$, Eq. (5) was evaluated from $n=0.5$, 1, and 2, which were the only cases where an analytical solution could be obtained. The resulting equation for γ was then fitted by the least-squares method to the data in Fig. 4 (excluding the Kr^+ and Xe^+ data) by varying the constants k and c, setting U_0 to 1 eV and β to 0.3.[7] The constants obtained by this procedure are given in Table I. For $n=1$, Eq. (5) leads to

$$\gamma = \frac{U_0}{2c}\left\{-1+\left[1+\frac{4ckD}{U_0^2}\right]^{1/2}\right\}\ , \tag{6}$$

which is plotted in Fig. 4 for the constants given in Table I. This gives a curve which is almost identical to Eq. (3), except for the lowest D, indicating that the model may indeed be appropriate. It is interesting to note that for $n=1$ a change in the surface barrier of 2.2 eV is predicted for the largest electron yields, which seems reasonable. The proportionally constant b depends slightly on n, but for metals it could be expected to be ~ 0.15,[32] which would give a rather large value of $a \approx 0.14$ Å^{-1} for $n=1$. However, for insulators the electron binding energy has to be taken into account, which lowers the expected value of a, and $0.15/k$ in Table I could be regarded as an upper limit of a.

For $n=0.5$, an even better fit to the data could be obtained, but the determined value of c then gives an unreasonably large change in U. A slightly inferior, but still acceptable fit, could also be obtained for $n=2$, indicating that the model is not very sensitive to the applied electron stopping power. In reality, n probably varies with ε, but since $n>0$ can be expected up to fairly high energies,

TABLE I. Constants derived from a least-squares fit of the equation for γ, obtained from Eq. (5), to the data in Fig. 4 assuming $\beta=0.3$. r is a coefficient giving the correlation between the fit and the data.

n	c (eV)	$0.15/k(>a)$ (Å^{-1} eV^{1-n})	r
0.5	2.2	0.053	0.997
1	0.088	0.14	0.994
2	0.071	0.062	0.981

the electron yield is, according to Eq. (5), still expected to increase more slowly with D than linearly. Altogether this clearly indicates that the proposed model is a reasonable one.

Since the electronic energy deposition will be much more spread out laterally for large angles of ion incidence than at normal incidence, it is somewhat surprising that the electron yield can be so well characterized solely by D, the total electronic energy deposition per unit depth. Actually, from the angular measurements, a dependence of the electron yield on D between $D^{0.69}$ and $D^{0.79}$ can be extracted for the individual ions; that is a slightly stronger dependence than the $D^{0.62}$ obtained for the normal incidence data only. This could be a manifestation of the larger distance in the electron-hole interaction at non-normal ion incidence.

B. Variations in γ close to the SiO_2/Si interface

A striking feature of the variations in γ close to the transition region, hereafter called peaks, is their dependence on ion mass and energy. The relevant parameter determining the magnitude of the peaks does not seem to be the electronic energy deposition, since no obvious correlation can be found in Fig. 1. However, in Fig. 5 it can be observed that the peak height increase with increasing ion energy, for similar ion masses, and increases with decreasing ion mass, for similar ion energies. This is roughly consistent with an increasing peak height with increasing ion velocity.

The velocity of 300-keV N^+ ions is $0.92v_0$ (v_0=Bohr velocity) which is comparable to typical electron velocities, whereas the velocity of 200-keV Xe^+ ions is $0.25v_0$. Since it was suggested that escaping electrons interact with the electronic excitations in the target, it is reasonable to expect that the time dependence of electronic excitations is important, particularly at the SiO_2/Si interface where there is an abrupt change in the electronic structure.

In Si, the liberated electrons can be assumed to move independently of the holes, since the mobility of holes is much higher than in SiO_2 and since the material used was n doped and there are conduction electrons available. Neither was a nonlinearity observed in $\gamma(D)$ for Si. There is possibly a net transport of electrons from Si into the oxide in the electron cascades during ion bombardment, due for example to an attractive force from the holes in the oxide. This would reduce the force that holes exert on escaping electrons in SiO_2 and, consequently, for films thin enough, enhance the electron yield, thus causing the peaks. For this effect to be noticeable, electrons must not necessarily escape from the Si substrate to the surface. It is sufficient if electrons from Si neutralize or screen holes within an interaction distance from electrons in the oxide, which can escape.

The ion velocity dependence of the injection efficiency cannot be explained simply by the time it takes for the ion to reach the Si substrate, since no peak would then be expected in $\gamma(70)$ for 200-keV N^+-ion bombardment, because no peak is observed in $\gamma(0)$ for 200-keV Kr^+-ion bombardment, and it takes about the same time for these ions to reach the Si substrate. A peak is clearly observed in $\gamma(70)$ for 200-keV N^+-ion bombardment, however, as is indicated by the depth dependence of $\gamma(70)/\gamma(0)$ in Fig. 6. However, it may be that the only time scale of importance for the injection of electrons is the time scale of the electron excitations close to the SiO_2/Si interface. The injection could be much more effective, for example, if electrons are excited on both sides of the interface simultaneously than if most holes in the oxide are screened before the electrons in Si are excited. The peak effect would then mostly depend on the ion velocity and not much on the angle of ion incidence, which is in qualitative agreement with the observations.

If the peak effect is due to a (partial) neutralization of holes in the oxide, $\gamma(70)/\gamma(0)$ is expected to increase in the peak region toward the value expected for a linear dependence of γ on D. That this is not the case was already noted in Sec. III (Fig. 6). However, since it takes a longer time before electrons are injected from the Si substrate into the oxide at a 70° ion incidence than at normal incidence, it is reasonable that the neutralization is more effective at normal ion incidence than at 70° incidence. Therefore, $\gamma(0)$ may increase faster than $\gamma(70)$, and the independence of $\gamma(70)/\gamma(0)$ on the peak effect may be the net result of two canceling processes.

Furthermore, if the suggested mechanism is responsible for the peaks, a continuous transition from no effect to a saturation, where the effect becomes independent of velocity, is expected. For 200- and 300-keV N^+ ions, a saturation may indeed have been reached since the peak heights are almost the same. By comparing Kr^+ with Xe^+ ion bombardment in Fig. 5, it can be seen that also at the other end of the velocities, the shape of the electron yield curves are approximately independent of ion velocity. At similar ion velocities and at saturation velocities, the peak effect could also be expected to increase with increasing electron yield, since the number of holes to neutralize increases with the electron yield. This is indeed what can be observed when comparisons are made between ions of roughly the same velocity, and it can also explain why only a small peak is observed for 200-keV He^+ ions (not shown). According to this argument, the peak would also be larger for 300- than for 200-keV N^+ ions, contrary to observations, even if the saturation velocity is reached. It is possible that saturation is also reached in neutralization efficiency.

V. CONCLUSIONS

It has been shown that the electron yield from SiO_2 is not linearly dependent on the expected electronic energy deposition at the target surface. Various mechanisms causing this nonlinearity have been discussed, and it was found that holes left behind by electrons liberated by the ion beam may cause the probability of escape to decrease with increasing electron emission and consequently with increasing electronic energy deposition. Furthermore, nonmontonous variations of the electron yield close to the SiO_2/Si interface could reasonably be explained by

electron injection from the Si substrate influencing the emission process at sufficiently high ion velocities.

A nonlinear dependence of the electron yield on the electronic energy deposition might possibly be observed for other materials as well, at large electron yields. For semiconductors with low hole mobility, the situation is qualitatively similar to that of insulators. In metals, the electron emission process is expected to be much faster than in insulators, and holes formed in the core of the atoms could possibly be sufficiently long-lived to influence the emission.

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