THE PHENOMENON OF ELECTRON ROLLOUT FOR ENERGY DEPOSITION
AND DEFECT GENERATION IN IRRADIATED MOS DEVICES**

Dennis B. Brown
Naval Research Laboratory
Washington, DC 20375-5000

Abstract

Energy deposition and defect generation in the gate oxides of MOS devices irradiated with 10 keV x-rays are analyzed. Particular attention is given to the role of secondary electrons produced by inelastic scattering and plasmon decay processes. It is shown that more than 50% of x-ray generated holes are produced by electrons of less than 100 eV. A mechanism, "electron rollout", which reduces hole generation in thin gate oxides is discussed. A concept of the hole production enhancement factor is introduced as a refinement of the commonly used absorbed dose enhancement factor. Results of calculations of enhancement factors based on these ideas are presented. These revised enhancement factors are about 20% smaller than previously calculated absorbed dose enhancement factors for oxides with thicknesses in the neighborhood of 50 nm.

Introduction

There is a growing use of x-rays of approximately 10 keV to test the radiation hardness of MOS devices. The proper use of such a technique may require an understanding of the energy deposition and defect production mechanisms which are active. For example, proper comparison of hardness testing results obtained using 10 keV x-rays with results obtained using Co-60 irradiation will require allowance for the energy dependent differences in the processes involved in the production of interface states and trapped holes.

One important aspect of this problem of energy dependent production processes is the non-equilibrium deposition of energy which is to be expected in the small volumes of material which are characteristic of MOS structures. In particular, it is expected that for irradiation with 10 keV x-rays there will be an enhancement of the dose in the thin gate oxides resulting from the influx of energy which was initially deposited in the adjacent Si. Calculations of the magnitude of this effect have been published previously. Brown has calculated average absorbed dose enhancement factors for energy deposition in SiO2 for several values of oxide thickness between 25 and 2000 nm.1 Calculations by Burke,2 using an independent technique,3 have given similar results. These calculations must be reconsidered in light of work of Ashley and Anderson which states that for electrons of less than 100 eV the mean free path for inelastic interaction in SiO2 may be an order of magnitude larger than the corresponding mean free path for Si.4 If it is correct that there is a relatively long mean free path in SiO2 as compared to that in Si it follows that, for the case of thin oxides, some energy deposition which had been previously thought to occur in SiO2 actually takes place in the adjacent Si.

Burke has suggested that this phenomenon, which reduces the absorbed dose in the SiO2 gate oxide, be called "rollout".2 It should be contrasted with normal absorbed dose enhancement phenomena which, for 10 keV x-ray irradiation, cause an increase of the dose deposited in SiO2. This phenomenon may serve to explain published data5 which appears to show smaller absorbed dose enhancement effects than those predicted by previous calculations.1-3

This paper will present the results of a calculation of the effect of electron rollout on the enhancement factors appropriate for use with 10 keV x-ray irradiation of MOS devices. First, a review will be given of an earlier calculation method in order to set the background for the calculation methodology and to single out, for consideration and improvement, a problem with that methodology. Secondly, the key role of low energy electrons in the generation of holes will be developed. Thirdly, the importance of considering the enhancement of hole generation rather than the enhancement of absorbed dose will be emphasized. Finally, the results of calculations of hole generation enhancement factors will be presented and compared with previous work.

Key Assumptions of Earlier Calculation

The energy loss scheme used in Ref. 1 is shown schematically in Fig. 1. Note that the photons deposit most of their energy as the kinetic energy of electrons. After that transfer of energy takes place it is the transport of electrons which must be treated; the initial photons are of no further concern. Note, in Fig. 1, that the energy lost from the primary electrons (as well as the energy remaining in the primary electrons after they have dropped to about 1 keV) was calculated to be deposited at the position within the device where the loss was calculated to occur. The principal justifications for this

![Fig. 1. Schematic representation of energy loss scheme used in energy deposition calculation.](image)

** This work was supported by the Defense Nuclear Agency through its Basic Mechanisms and Hardness Assurance programs and also by the Strategic Defense Initiatives Program.

U.S. Government work not protected by U.S. Copyright.
procedure were the following assumptions and observations: (a) most of the energy loss is transferred to low energy secondaries -- these were assumed to have a negligible range, and (b) the transport solution was observed to be insensitive to the cutoff energy in the neighborhood of 1 keV.

For quite thin oxides (20-40 nm), justification of the results of Ref. 1 required a somewhat different analysis. In this case the range of secondary electrons might not be small in comparison with the thickness of the oxide. However, in this case, the electron density in the SiO₂ layer is dominated by primary electrons coming in from the neighboring Si layers. As a result the following sequence of reasoning is appropriate. The electron densities of the primary electrons in the Si and SiO₂ layers are nearly identical and thus the electron densities of the secondary electrons are nearly identical. Because of this the exchange of secondary electrons between the two materials has little effect on the electron densities. The energy deposition by the secondary electrons is given by the product of the electron density and the electron stopping power. Moreover, the electron stopping power for Si and SiO₂ were thought to be very similar. From the above qualitative argument it can be deduced that for thin oxides the dose in SiO₂ is very nearly that in the adjacent Si.

**Hole Production by Low Energy Electron**

The above analysis for the energy deposition in quite thin oxides is plausible and is in accordance with the predictions of cavity theory. However the work of Ashley and Anderson⁶ cast doubt on this reasoning for the case of thin oxides in a Si/SiO₂/Si sandwich. The problem is not that cavity theory is fundamentally wrong but, rather, that the implicit assumption that electron stopping powers are only slowly varying functions of atomic number is incorrect in this case. Fig. 2 (based on Ref. 4) shows the results of calculations by Ashley and Anderson for the mean free path for inelastic interaction in SiO₂ and in Si. Note in Fig. 2 that electrons of 500 eV and above show nearly the same mean free path for inelastic interaction in Si and SiO₂. This is in accordance with the expectations summarized in the previous paragraph. However, the situation is clearly different for electrons of less than 100 eV. Such electrons may be said to find it relatively difficult to deposit energy in SiO₂. As a result, secondary electrons moving from the Si into the SiO₂ will have a relatively low probability of generating holes while, conversely, secondary electrons moving from the SiO₂ into the Si will have a relatively high probability of generating holes. It is likely, based on the above reasoning, that the production of holes will be enhanced in Si and reduced in SiO₂ in the vicinity of the Si/SiO₂ interface.

This process for the reduction of hole production in SiO₂ can be quantitatively significant only if it is true that a substantial fraction of the holes produced in SiO₂ are produced by electrons of less than 100 eV. A simplified electron energy loss cascade calculation has been performed to determine the truth of this hypothesis.

In this energy loss cascade calculation, primary electrons of 10 keV are followed as they lose energy to ionization processes and to plasmon generation. The generation of secondary electrons is accounted for and they too are followed as they lose energy. The desired result of this calculation is the number of holes which are produced by electrons of 10 keV to 3.1 keV, electrons of 3.1 keV to 1 keV, etc. Additional details of this calculation are given in Appendix A. The results of this calculation are presented in Table I. It should be emphasized that Table I presents the number of holes produced by all electrons lying in a given energy range. This includes the primary electron and all of the secondary electrons which were generated by that primary electron.

It will be observed that the results of Table I suggest that 68% of the holes are produced by electrons of 100 eV or less energy. Though these results are intended to be taken as approximate, the conclusion seems unavoidable that a large fraction of holes are produced by low energy electrons. These results are made qualitatively reasonable by the fact that the energy loss processes produce a large number of electrons at low energy.

**Table I**

<p>| HOLES PRODUCED BY ELECTRONS OF GIVEN ENERGY RANGES PER INITIAL 10 keV ELECTRON |
|---------------------------------|-----------------|</p>
<table>
<thead>
<tr>
<th>LOSS PROCESS</th>
<th>HOLES PRODUCED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. electrons drop from 10000 to 3162 eV</td>
<td>27.11</td>
</tr>
<tr>
<td>2. electrons drop from 3162 to 1000 eV</td>
<td>40.79</td>
</tr>
<tr>
<td>3. electrons drop from 1000 to 316 eV</td>
<td>64.00</td>
</tr>
<tr>
<td>4. electrons drop from 316 to 100 eV</td>
<td>83.31</td>
</tr>
<tr>
<td>5. electrons drop from 100 to 31.6 eV</td>
<td>89.14</td>
</tr>
<tr>
<td>6. electrons drop from 31.6 to 10 eV</td>
<td>104.30</td>
</tr>
<tr>
<td>7. production of holes by 13 eV electrons**</td>
<td>74.55</td>
</tr>
<tr>
<td>8. production of holes by 10 eV electrons</td>
<td>180.01</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>663.20</td>
</tr>
</tbody>
</table>

**13 eV electrons are produced by one of the plasmon decay processes (see App. A)**
of secondary electrons, and that secondary electrons tend to be of substantially lower energy than the primary electron which produced them.

As additional support for the methods of Appendix A, it should be noted that the results of Table I suggest an effective hole formation energy of 15 eV. This is in fair agreement with experimentally obtained values and with the calculations of Ausman and McLean.7 The calculations of Ausman and McLean make the assumption that almost all energy loss is to plasmon generation. In contrast, the calculations of Appendix A attempt to apportion energy loss between plasmon generation and direct electron-hole generation.

Enhanced Effects in MOS Devices

It is necessary to estimate the magnitude of the change in radiation induced effects in MOS devices caused by non-equilibrium dose deposition processes. In Ref. 1 this was done by calculating the absorbed dose enhancement factor. The average absorbed dose enhancement factor in a SiO2 layer is defined as the average absorbed dose in the layer divided by the equilibrium absorbed dose, where the equilibrium absorbed dose is the absorbed dose in a layer which is sufficiently thick that it is essentially free of the effects of adjacent materials. The results of the calculations of Ref. 1 for a Si/SiO2/Si sandwich are shown in Fig. 3 (solid line). An important modification of the enhancement factor will be adopted in the present paper. An enhancement factor for a SiO2 layer will be defined which is the average energy deposited in holes in the layer divided by the energy which would be deposited in holes under equilibrium conditions. The principal distinguishing feature of this enhancement factor is that it specifically excludes from consideration energy deposition by electrons which are of too low an energy to produce electron-hole pairs. Such electrons lose energy principally to the production of phonons. This definition of an enhancement factor corresponds to the tentative assumption that the energy deposition by such subexcitation electrons is of no importance to the production of radiation induced interface states and trapped holes in MOS devices.

The calculation of this hole production enhancement factor has been performed using electron transport codes based on those described in Ref. 1. The principal modifications to the codes of Ref. 1 include (a) the ability to use tabular input for the energy loss data, (b) the ability to generate and track secondary electrons, and (c) the ability to handle the generation and decay of plasmons. Further details of the program modifications are provided in Appendix B.

Calculations were performed beginning with a monochromatic incident beam of 8 keV photons. The resulting primary and secondary electrons were followed down to between 9 and 10 eV, and the energy deposited to hole production was determined. Calculations were performed for Si/SiO2/Si sandwiches with oxide thicknesses of 28 and 46 nm. In addition, a calculation was performed for a pure SiO2 specimen (no adjacent Si layers) to provide the equilibrium value for energy deposited to hole production.

The results of calculations of the hole production enhancement factor obtained using the transport code are shown in Fig. 3 (circles). The dashed line through the experimental points has been added to guide the eye, and is speculative at this point. It will be noted that these hole production enhancement factors are about 20% lower than the average absorbed dose enhancement factors from Ref. 1.

The above results are in good agreement with the recent experimental work of Dozier et al.8 On the other hand, the above results are somewhat lower than earlier experimental work of Dozier et al.9 which appeared to be in agreement with the results of Ref. 1. However, Ref. 8 represents the current best opinion of those authors on this subject.

The above results should, in addition, be compared with the results of Fleetwood et al.5 Those researchers showed radiation effects for x-ray irradiation which were about 15% less than those they obtained with Co-60 irradiation. Their results are in the wrong direction to be explained by the enhancement effects treated in the present paper. That is to say, dose enhancement effects to be expected from x-ray irradiation of MOS devices would result in an increase in radiation effects, not a reduction. It is not clear at this time what physical mechanisms lie behind the results of those researchers.

The above results are also in approximate agreement with the recent experimental work of Benedetto and Boesch,10 although a detailed comparison cannot be made since Benedetto and Boesch used Al gate devices for their charge generation measurements while the calculations of the present paper are a better match to Si gate devices.

Monte Carlo calculations by Hamm11 show an enhancement factor of about 1.25 for a 50 nm oxide. It is believed that his result is lower than the results of this paper because he calculated the absorbed dose enhancement factor, rather than the hole production enhancement factor. It is to be expected that the absorbed dose enhancement factor is smaller. This can be shown to follow from the likelihood that
any sub-excitation electrons left in the SiO₂ at the end of hole production will not deposit their energy in the SiO₂ but, rather, will deposit their energy in the adjacent Si. The argument is as follows. If we define

\[ F_d = \frac{(E_h)^{\text{layer}} + (E_{se})^{\text{layer}}}{(E_h)^{\text{equilib}} + (E_{se})^{\text{equilib}}} \]

and

\[ F_h = \frac{(E_h)^{\text{layer}}}{(E_h)^{\text{equilib}}} \]

where \( F_d \) is the absorbed dose enhancement factor, \( F_h \) is the hole production enhancement factor, \( E_h \) is the energy deposition to holes, and \( E_{se} \) is the energy deposition by the sub-excitation electrons. The subscript "layer" indicates energy deposition in the oxide layer, while the subscript "equilib" indicates energy deposition under equilibrium conditions. Now if it is true that sub-excitation electrons have a negligible probability for depositing energy in a thin layer of SiO₂ bounded by layers of Si, then it follows that

\[ \frac{F_h}{F_d} = \frac{(E_h)^{\text{equilib}} + (E_{se})^{\text{equilib}}}{(E_h)^{\text{equilib}}} \]

which completes the proof that for thin oxide layers \( F_h \) is larger than \( F_d \).

Conclusions

It has been shown that electron rollout should reduce absorbed dose enhancement in Si/SiO₂/Si structures. Evidence has been presented that hole production enhancement factors are about 20% smaller than the previously presented absorbed dose enhancement factors for oxides with thicknesses in the neighborhood of 50 nm. Evidence has been presented that more than 50% of holes are produced by electrons of less than 100 eV.

Acknowledgements

Many thanks to Ed Burke for useful conversations on this subject. Thanks also to Bob Hamm for the privilege of seeing the results of his calculations prior to publishing.

APPENDIX A - A SIMPLIFIED ELECTRON ENERGY LOSS CASCADE CALCULATION

The results for hole generation presented in Table I were obtained using a simple energy loss cascade calculation based on a computer spread sheet. The calculation considered only the energy loss processes for the electrons. That is, the transport of the electrons from position to position was ignored. Further, the calculation was done for bulk SiO₂. That is, no effects of adjacent Si layers were included. The algorithm used for the calculation is summarized as follows:

1. Energy bins: The results of energy loss processes were treated in half-decade jumps. One electron was started in the 10000 eV electron bin. The energy loss processes involved in this electron dropping to 3162 eV were treated in two steps. Step A: Secondary electron production was also considered, and appropriate numbers of secondary electrons were added into the electron bins at 3162, ..., 10 eV. Step B: Generation of plasmons was considered, and appropriate numbers of plasmons were added to a plasmon bin. Steps A and B were then repeated, starting with the electrons in the 3162 eV electron bin, and so on.

2. Secondary electron energies: The secondary electrons were deposited evenly in equal logarithmic intervals down to 31.6 eV. This corresponds to electron scattering according to the Rutherford cross section. It should be noted that this secondary electron production mechanism results in a predominance of low energy secondary electrons. The secondaries produced by the 31.6 eV electrons were deposited in the 10 eV bin. The distribution of secondary energies just outlined is in approximate agreement with the calculations of Ritchie and Anderson.¹²

3. Fraction energy loss to plasmons: It is necessary to apportion the energy losses between plasmon generation and ionization processes. For this calculation the fraction of plasmon interactions as compared to direct electron-hole generation interactions was based on the calculations of Ritchie and Anderson.¹² Specifically, the ratio of the inverse mean free path for plasmon generation to the i.m.f.p. for direct electron-hole pair generation were taken to be 3, 2.5, 2, 1.5, 1, .7, 0, and 0 at energies of 10000, 3162, 1000, 316, 100, 31.6, 13, and 10 eV, respectively.

4. Plasmon decay: One third of the plasmons decay to produce a hole of 11 eV. In this case, a secondary electron of 13 eV has sufficient energy to produce an additional electron-hole pair. Two thirds of the plasmons decay to produce a hole of 17 eV. These approximations are based on the work of Ausman and McLean.⁷

5. Hole energies: In distributing the energy loss to electron-hole pair production an average hole energy was used. It follows from 4 (above) that the average hole energy is about 15 eV. This number was used except for hole production by 13 eV and 10 eV electrons, where the minimum hole production energy of 9 eV was used. This number is in accordance with the SiO₂ band gap.

APPENDIX B - MODIFICATIONS TO THE TEP TRANSPORT PROGRAM

The TEP transport programs are a series of programs which handle electron transport, x-ray generation, and x-ray deposition.¹³¹⁴ These programs handle electron transport by using a numerical solution of the Boltzmann equation. The materials being treated are modeled as a sandwich, i.e. a stack of planar slabs.

The TEP6 and TEP7 programs have been used as reported in Ref. 1 to calculate energy deposition, and thus absorbed dose enhancement. For the present paper a new program, based on the TEP7 program, has been produced in order to track energy deposition down to the minimum hole generation energy in SiO₂.

The TEP7 program already had the ability to accept, as input to the electron transport process, a file containing electrons of an arbitrary number of energies. Because of the existence of this mechanism it was straightforward, in principle, to modify the program to handle secondary electrons. The transport process begins with the electrons of highest energy and, as the electrons lose energy, additional electrons of increasingly lower energy are introduced from the electron input file until it is emptied. As secondary electrons are generated they are put into the electron input file, to be re-introduced into electron transport when the transport process has dropped to the appropriate energy.
Further details of the modifications to the TEP7 program are as follows:

1. Secondary electron energies: The secondary electrons were deposited evenly in equal logarithmic intervals down to 10 eV. This corresponds to electron scattering according to the Rutherford cross section. This distribution for the secondary electron energies is in approximate agreement with the calculations of Ritchie and Anderson.  

2. Fraction energy loss to plasmons: Handled as described in App. A.

3. Plasmon decay: Handled as described in App. A.

4. Hole energies: An average hole energy of 15.02 eV was used. See App. A for discussion

5. Electron energy loss: electron stopping power data from the Oak Ridge National Laboratory group were used in tabular form. 

References


2. E. A. Burke, Mission Research Corporation, private communication.


11. R. Hamm, Oak Ridge National Laboratory, presented at a meeting of the Hardness Assurance Committee of the NASA/SD Space Parts Working Group, San Jose, 29 Jan 86.