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May 1996

KIX Preprint 96-18
Japan

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Characterization of an ONO-stacked insulator film for a silicon micro-strip detector

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ABSTRACT

A semi-empirical model for an ONO-stacked insulator film is presented together with its implications. The model covers ONO, ON, and NO films as well as single-layered SiO$_2$ and Si$_3$N$_4$. We eventually present an assessment for estimating the lifetime of an ONO-stacked insulator film for a given configuration.

1. Introduction

We have been developing a double-sided silicon micro-strip detector
as a part of the KEK B-factory experiment, BELLE, where a reliable integrated capacitor is an essential part in terms of a technical breakthrough. The thickness of the insulator film which we are interested in is about 200 nm, on which a 50-to-100 V bias voltage is applied. An ideal silicon dioxide flows a very small current and withstands a high electric field. In reality, point-like defects existing in the dioxide gather currents to mediate a breakdown earlier than the perfect dioxide. In order to compensate for the point-like defects, an ONO stacked insulator film has attracted attention as a possible candidate for an integrated capacitor of the double-sided silicon micro-strip detector. Since silicon nitride has a higher dielectric constant than does silicon dioxide, a sandwiched structure is favorable for making an integrated capacitor. In order to explore the technology of an electrically erasable programmable read-only memory, many studies have been made concerning silicon dioxide and silicon nitride regarding their current-conduction nature and breakdown properties. These studies can guide our work. In order to make sure of the superiority of an ONO insulator film, we should explore the current-conduction properties and construct an electrical model of the ONO film. Starting from a single-layered silicon dioxide and silicon nitride, we went forward to study a SiO$_2$–Si$_3$N$_4$-stacked insulator film (ON or NO, depending on the dioxide location on the cathode or on the anode, respectively), and confirmed the basic principles for the current conduction in the insulator film. We eventually reproduced the current flow in a SiO$_2$–Si$_3$N$_4$–SiO$_2$-stacked (ONO) insulator film by a semi-empirical model developed in this study. Since the experimental aspects, such as the preparation and/or measurement procedures, were described in ref. 6, we concentrate here on the theoretical aspects and their implications. Instead of going into detail concerning the breakdown nature, we examined a low-current and steady-state condition in order to estimate the lifetime for a given configuration of a stacked insulator film, where we employed a known electron-to-hole current ratio. Chapter 2 describes the theoretical background of the conduction model...
of the insulator film together with some comparison with experimentally observed data. In chapter 3 we apply the model to ON and ONO films and show an assessment to design a long-life integrated-capacitor under a high electric field. Chapter 4 summarizes discussion.

2. Electronic characteristics of the insulator film

2.1. Cathode tunneling, Fowler-Nordheim emission

The major carrier injection at the cathode interface between silicon and silicon dioxide is due to a tunneling effect through a SiO₂ potential barrier. Figure 1 (a) shows a simplified band diagram of the Si – SiO₂ interface at the cathode. The current which flows due to a tunneling effect is called Fowler-Nordheim emission, based on the original work by Fowler and Nordheim. The tunneling-current density has been calculated in an application with the WKB approximation, which yields

\[
J_{ox} = \frac{q^2 E_{ox}^2 m}{8\pi \hbar \phi_b n^*} \exp\left(\frac{-4\sqrt{2m^*}(\phi_b)}{3\hbar E_{ox}}\right),
\]

where \( \phi_b \) is the barrier height, \( m \) the electron mass, \( m^* \) the effective carrier mass, \( E_{ox} \) the electric field in the silicon dioxide, \( q \) the electronic charge, \( \hbar \) Planck’s constant, and \( \hbar \) Planck’s constant divided by \( 2\pi \). The ratio of the effective electron carrier mass \( (m^*) \) to the free-electron mass \( (m) \) is taken to be 0.42 throughout this work. We can find that the Fowler-Nordheim current has no temperature dependence, which is a distinct characteristic when compared with the Poole-Frenkel emission discussed later. There exists a more rigorous calculation which includes barrier-height lowering due to the image-force effect, which is out of scope of the present work. Figure 2 (a) shows the \( J_{ox} - V \) characteristics of the SiO₂ insulator films. While it appears that there exists a large dependence on the insulator thickness, we can obtain a universal view once we take the horizontal axis as \( E_{ox} \), as shown in Figure 2 (b). We should make a note here concerning the direction of the current flow. For the first three samples (\( t_{ox} = 9.9, 37.4 \), and 205 nm), the electrons are emitted from n-type bulk silicon (n⁺), while in the fourth sample (\( t_{ox} = 205 \) nm) FN-emission occurs at n-type poly-silicon located at the top of the capacitor structure. Employing the data points for \( J_{ox} < 10^{-6} A/cm^2 \), we obtained barrier heights of 3.088±0.006 eV and 3.180±0.013 eV for electron injection from n-type bulk silicon and an n-type poly-silicon electrode, respectively, which are consistent with the known result. When we take the horizontal axis as \( 1/E_{ox} \) and the vertical axis as \( J_{ox}/E_{ox}^2 \) in the log scale, the data for the Fowler-Nordheim current are on a unique straight line, as shown in Figure 2 (c), which is called an FN-plot. Employing this FN-plot, we can quickly identify whether the current in an insulator film is according to the Fowler-Nordheim emission or not.

2.2. Poole-Frenkel conduction

After penetrating through the potential barrier of silicon dioxide, the electrons are accelerated by an electric field and de-accelerated via an interaction with the phonon field. As long as the electric field is still moderate and the dioxide is sufficiently thin, the electrons cannot acquire sufficient energy for an avalanche multiplication before arriving at the interface with the other material. If we choose a nitride as an accompanying material, the electrons have no way but to annihilate at the interface, since the major carrier-conduction mechanism in the nitride is due to holes. This is one of the reasons for employing a dioxide-nitride stacked insulator film as a reliable integrated capacitor. Before considering a stacked insulator film we discuss the properties of a single-layered nitride.

The current conduction in the nitride is characterized as a repetitive sequence of capture and thermal emission of holes to/from the trap site, i.e. the Poole-Frenkel effect. When we apply an electric field of \( E_{mn} \) to the nitride, the current density is described as

\[
J_{in} = C_{PF} E_{mn} \exp\left(-\frac{q}{kT}(\phi_t - \eta \beta \sqrt{E_{mn}})\right),
\]

where \( \phi_t \) is the potential depth for the traps, \( k \) the Boltzmann constant, \( T \) the absolute temperature in Kelvin, \( \eta \) the correction factor for a barrier-height lowering,
and \( \beta \) represents the barrier-height lowering effect, which is described as

\[
\beta = \sqrt{\frac{q}{\pi \varepsilon_0 \varepsilon_n}}.
\]

(2.3)

\( C_{PF} \) is the constant which depends on the detailed nature of the \( Si_3N_4 \) film, which has an apparent dependence on the nitride thickness (\( t_n \)) as

\[
C_{PF} = J_0 \cdot \exp \left( -\frac{t_n}{t_c} \right),
\]

(2.4)

where \( J_0 \) provides a geometry-independent parameter for the Poole-Frenkel emission, \( t_n \) is the thickness of the nitride film, and \( t_c \) is a sort of characteristic length of the \( Si_3N_4 \) film. A rigorous nature of the thickness dependence has been explained by taking into account of the space-charge effect.\(^{[9]} \) The most shallow potential depth (\( \phi_i \); measured from the valence band) for holes is known to be 1.3 eV,\(^{[9]} \) which concerns the current conduction in \( Si_3N_4 \). Figure 3 (a) shows the \( J_{an} - V \) characteristics for nitride films. As in the case for the FN-current, we try to show the characteristics in the \( J_{an} - E_{an} \) relation in Figure 3 (b). The data points do not gather on a single curve, which still have a dependence on the thickness of the insulator. The first three samples (\( t_n = \{84, 157, 298 \} \) nm) are fabricated on a n-type bulk silicon (\( n^+ \)), while the last sample (\( t_n = 157 \) nm) was fabricated on a p-type bulk (\( p^+ \)). As for the first samples, the bulk silicon was taken as the cathode, while for the last sample the bulk silicon was taken as the anode. We found for either samples with \( t_n = 157 \) nm that the electrode material, or the direction of the current flow, did not affect the characteristics of the current flow. Employing the data points for \( J_{an} < 10^{-6} \) A/cm\(^2 \), we obtained \( J_0 = \{5.7_{-1.4}^{+1.3}\} \times 10^{-6} \) A/V cm, \( t_c = 54.9_{-4.3}^{+8.5} \) nm, and \( \eta = 1.33 \pm 0.01 \). When we took a horizontal axis as \( \sqrt{E_{an}} \) and a vertical axis as \( J_{an}/E_{an} \) in the log scale (Figure 3 (c)), the plots for the Poole-Frenkel current ride on straight lines as long as the temperature is kept constant, which is called a PP-plot, and provides a quick method to identify the Poole-Frenkel current. We note here that a single-layered nitride film is useless as an insulator film. Once the current flow begins to dissipate some energy, the current flow is amplified due to its Joule heating to eventually reach a destructive result.

2.3. Anode tunneling, Fowler-Nordheim emission of hole

We consider here a two-layered structure comprising silicon dioxide and silicon nitride, where the silicon dioxide is located on the anode side, i.e. the NO configuration. We assume that the carrier emission through the anode dioxide is due to a hole tunneling effect. Figure 1 (b) shows a simplified band diagram between the \( Si - SiO_2 \) interface at the anode side. Figure 4 (a) shows the current versus the terminal-voltage characteristics. Figure 4 (b) takes the horizontal axis as a nominal electric field, defined as

\[
E_{nom} = \frac{V}{t_n + t_{ox}},
\]

(2.5)

where the thickness of the dioxide is indicated as \( t_{ox} \) to explicitly show that the dioxide is located at the anode side. Two samples are shown in the figure: one has a dioxide of \( t_{ox} = 4.4 \) nm underneath the n-poly electrode; the other has a dioxide of \( t_{ox} = 6.3 \) nm on the p-type bulk silicon (\( p^+ \)). The I-V characteristics are little affected by the electrode material. A small discrepancy between the two can be explained in terms of the total thickness of the material, i.e. \( t_n + t_{ox} \). The equation used to set the hole current is identical to Eq (2.1), except for the barrier height and effective mass. The barrier height and effective mass we employed, were \( \varphi_h = 3.8 \) eV and \( m^*/m = 0.63 \), respectively. Following an iterative procedure described in the appendix, we could simultaneously set \( E_{ox}, E_{an}, J_{ox} = J_{an} \) and the interface charge (\( Q^\varphi \)) for a given terminal voltage (V). The theory did not necessarily follow the data points, except for at the medium range around 5 to 8 MV/cm. The excess for the low current region could be explained in terms of trap-assisted tunneling, which is beyond the scope of the present work. The discrepancy for a higher electric field is possibly due to the Joule-heating effect.
We find later that the behavior of the ONO-stacked insulator film is well described by these parameters.

3. Characterization of the ONO film

3.1. ON and ONO-stacked film

The model parameters used to characterize the dioxide, and the nitride films are listed in Table 1. We would like to show that the electric characteristics of ON and ONO insulator films are well reproduced without any other parameters, being listed in Table 1. Figure 5 (a) shows the I-V characteristics for the ON films. Three samples are given: \( t_{ox} = 6.3, 19.5, \) and 37.4 nm with \( t_{nm} = 157 \) nm. The electrons are emitted from the n⁺ bulk for these samples. For a current density below 1 \( \mu A/cm^2 \), the curves follow the data points very well. Figure 5 (b) is a plot which takes a nominal electric field as the horizontal axis. The nominal electric field is defined as

\[
E_{nom} = \frac{V}{t_{ox} + t_{nm}}.
\]

The three curves behave in a similar way, except for a minor discrepancy due to the dioxide thicknesses. Figure 6 (a) shows the I-V characteristic of ONO-stacked films. Two samples are given: one has a thick cathode, \( t_{ox} = 37.4 \) nm (and thin anode, \( t_{ox} = 4.4 \) nm); and the other has a thin cathode, \( t_{ox} = 4.4 \) nm (and thick anode, \( t_{ox} = 37.4 \) nm). The thickness of the nitride is common for both samples, i.e. \( t_{nm} = 157 \) nm. Figure 6 (b) employs a nominal electric field as the horizontal axis. The nominal electric field for an ONO film is defined as

\[
E_{nom} = \frac{V}{t_{ox} + t_{nm} + t_{ox}^e}.
\]

The two data samples are reproduced with the model parameters without any additional assumptions. The two curves in the figure appear to be separated too much from each other, which is not due to the film configuration, but to the electrode material. The thinner cathode dioxide is located underneath the poly-silicon electrode, while the thicker cathode dioxide is on the silicon bulk. The difference in the barrier height for the silicon bulk and the poly-silicon explains the apparently large difference between the two curves. In the iterative procedure to set \( J_{ox}, J_{ox}^e, E_{ox}^e, E_{ox}, \) and \( E_{ox}^e \), we simultaneously obtain interface charges of \( Q^e \) and \( Q^a \), which are essential to maintaining a current balance between the dioxide and the nitride. Figure 7 (a) and (b) show the charge densities accumulated at the cathode and anode interfaces. We find here general tendencies: the signs of the charges are almost negative for a wide range of bias voltages; and the charge density at the cathode interface increases for higher bias voltages, which works to relax the electric field of the cathode dioxide; the charge density at the anode interface decreases for higher voltages, which works to relax the electric field of the anode dioxide. We mention here that the accumulated negative charge of the ONO film may assist the band-to-band tunneling around the field-plate structure, as discussed in ref. 1. Figure 8 (a) and (b) show the electric fields for each material of the stacked film. We find some general tendencies: the electric field in the nitride is always smaller than the nominal electric field, while the fields in the dioxide are always higher than the nominal one; the electric field in the anode dioxide is much higher than the cathode dioxide, which comes from the fact that the barrier height of the cathode emission is smaller than the hole emission from the anode dioxide, and that the carrier effective mass for the cathode tunneling makes the tunneling easier than the anode dioxide.

3.2. Long-term Reliability

For silicon dioxide thinner than 80 nm, it is known that the breakdown of the dioxide film has a strong correlation with the total hole-charge flowing through the dioxide. The integrated hole current before breakdown was observed to be characterized as a single number, i.e. 0.1 Coulomb/cm²µm, whatever the electric field was. According to the measurement appearing in ref. 19, we derived an
empirical formula as for the hole current ($J_h$) to the FN current ($J_{e2x}$) ratio as

$$\frac{J_h}{J_{e2x}} = t_{e2x}^{3.76 \cdot 10^{-7.54}},$$  \hspace{1cm} (3.3)

where $t_{e2x}$ ($t_{e2x}^0$ in an exact notation), was measured in nm. While this formula seems to well reproduce the data points around 8 to 10 MV/cm, we extrapolated so as to use the formula down to 4 MV/cm. We assume that the breakdown for the ONO film is due to a deterioration of the cathode dioxide. Figure 9 shows the lifetime of the insulator films before a breakdown in terms of the thickness of the cathode dioxide. The barrier height for FN-emission was taken as 3.088 in order to take the worse case. The straight lines show the life-to-current density relations for fixed thicknesses of the cathode dioxide. A trivial conclusion is that a higher current operation shortens the lifetime before a breakdown. A non-trivial conclusion results from the curved lines, where the total film thickness is kept constant at 200 nm with $t_{e2x}^0=5$ nm, while the compositions of $t_{e2x}$ and $t_{e2x}^0$ are varied. We find that the lifetime before a breakdown quickly becomes stretched longer for a thinner dioxide of $t_{e2x}^0=40$ nm or less. The curves are drawn for constant bias voltages of 90, 100, 110, and 120 Volts. As long as it is operated below 100 V, an ONO insulator film with $t_{e2x}^0=40$ nm lasts for more than 25 years, which is acceptable for the KEKB experiment.

4. Summary

Starting from an analysis of single-layered insulator films, we obtained a comprehensive electrical model of a stacked insulator film for ON, NO, and ONO configurations. We experimentally extracted nine model parameters using existing FN-emission and PF-conduction theories as a guide. Assuming that the origin of the deterioration of the silicon dioxide is closely correlated with the hole current in the dioxide, we have drawn a diagram for the lifetime versus the leakage current. From this diagram we know that the thinner cathode dioxide with a relatively thick nitride has superior characteristics for the lifetime before a breakdown.

**APPENDIX A**

**Iterative procedure** Taking the example of an ONO film, we consider here an iterative procedure used to set a solution for the electric fields as well as the conduction currents. The electric field in the dioxide located at the cathode side is described as

$$E_{e2x} = \frac{Q^c}{\epsilon_{2x}} + \frac{Q^a t_{e2x}}{\epsilon_{e2x}} + \frac{Q^c t_{e2x}^0}{\epsilon_{e2x} X_{tot}},$$  \hspace{1cm} (A.1)

where

$$X_{tot} = t_{e2x} + t_{e2x}^0 \frac{\epsilon_{e2x}}{\epsilon_{e2x}} + t_{e2x}^a.$$  \hspace{1cm} (A.2)

Here, $t_{e2x}^a$, $t_{e2x}$, and $t_{e2x}^0$ are the thicknesses of the dioxide on the cathode side, nitride, and the dioxide on the anode side, respectively. $Q^c$ and $Q^a$ represent the interface charge densities assumed at the cathode-side dioxide-nitride interface and the anode-side interface, respectively. In this notation the electric fields in the nitride, and in the dioxide at the anode-side, are written as

$$E_{an} = \frac{Q^c t_{e2x}^0 + Q^a t_{e2x}}{\epsilon_{e2x} X_{tot}},$$  \hspace{1cm} (A.3)

and

$$E_{an} = \frac{Q^c t_{e2x}^0 + Q^a t_{e2x}}{\epsilon_{e2x} X_{tot}} - \frac{Q^c t_{e2x}^0}{\epsilon_{e2x} X_{tot}},$$  \hspace{1cm} (A.4)

respectively. Once a terminal voltage ($V$) is given, we can first set the electric field with the assumption of a zero interface charge. The electric fields are employed as inputs to calculate the conduction current: $J_{e2x}$, $J_{an}$, and $J_{e2x}^a$. Assuming that the imbalance of the currents causes an accumulation of either in positive or negative interface charges, we move $Q^a$ and $Q^c$. We can then update the electric fields again. The iterative procedure should continue until $J_{e2x}$, $J_{an}$, and $J_{e2x}^a$ become equalized for a given tolerance.
ACKNOWLEDGEMENTS

The present work was part of a developmental effort to build a silicon microvertex detector for the BELLE collaboration. We sincerely appreciate suggestions and advice from the SVD group members. The directors of the physics department of KEK (S. Iwata, F. Takasaki, M. Kobayashi, and K. Nakamura) are acknowledged for their encouragement during this work.

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TABLE CAPTIONS

1: Summary of the model parameters
Table 1. Summary of the model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>Dielectric constant for silicon dioxide</td>
<td>( \epsilon_{ox} )</td>
<td>3.9</td>
</tr>
<tr>
<td>Dielectric constant for silicon nitride</td>
<td>( \epsilon_{sn} )</td>
<td>7.5</td>
</tr>
<tr>
<td>Barrier height for cathode tunneling</td>
<td>( \phi_b )</td>
<td>3.088 eV</td>
</tr>
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<td>at the Si/SiO(_2) interface</td>
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</tr>
<tr>
<td>at the nPoly/SiO(_2) interface</td>
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<td>Effective carrier mass for electron</td>
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<tr>
<td>for hole</td>
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<tr>
<td>Hole trap energy in silicon nitride</td>
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</tr>
<tr>
<td>Correction for barrier height lowering</td>
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<td>Characteristic length for the PF conduction</td>
<td>( t_c )</td>
<td>54.9 nm</td>
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<tr>
<td>Coefficient for Poole-Frenkel emission</td>
<td>( J_0 )</td>
<td>( 5.7 \times 10^{-6} ) A/Vcm</td>
</tr>
<tr>
<td>Barrier height for anode tunneling</td>
<td>( \phi_a )</td>
<td>3.8 eV</td>
</tr>
</tbody>
</table>

**FIGURE CAPTIONS**

1) Simplified band diagram at the Si – SiO\(_2\) interface
   (a) for cathode tunneling
   (b) for anode tunneling

2) a) \( J_{ox} - V \) characteristics of the SiO\(_2\) insulator film
   The curves in the figure come from Eq (2.1).
   b) \( J_{ox} - E_{ox} \) characteristics
   c) FN-plot

3) (a) \( J_{sn} - V \) characteristics of the Poole-Frenkel conduction
   The curves in the figure come from Eq (2.2).
   (b) \( J_{sn} - E_{sn} \) characteristics
   (c) PF-plot

4) (a) I-V characteristics for a dioxide-to-nitride current flow
   (b) \( I - E_{nom} \) characteristics

5) (a) I-V characteristics of the ON-stacked insulator film
   (b) \( I - E_{nom} \) characteristics

6) (a) I-V characteristics of the ONO-stacked insulator film
   (b) \( I - E_{nom} \) characteristics

7) Charge on the interfaces for
   (a) \( t_c = 37.4 \) nm, \( t_{sn} = 157 \) nm, \( t_{ox} = 4.4 \) nm
   (b) \( t_c = 4.4 \) nm, \( t_{sn} = 157 \) nm, \( t_{ox} = 37.4 \) nm

8) Normalized electric field of each layer for
   (a) \( E_{ox} = 37.4 \) nm, \( E_{sn} = 157 \) nm, \( E_{ox} = 4.4 \) nm
   (b) \( E_{ox} = 4.4 \) nm, \( E_{sn} = 157 \) nm, \( E_{ox} = 37.4 \) nm

9) Lifetime of the ONO insulator film versus current density on the cathode dioxide
A) Cathode tunneling

B) Anode tunneling

Figure 1
Interface charge in $10^{12} q/cm^2$

Normalized electric field by $V/(t_{ox} + t_{sn} + t_{ox})$

Figure 7 b)

Figure 8 a)
Normalized electric field by $V/(t\text{_{ox}}+t\text{_{sn}}+t\text{_{ox}})$

Life time before breakdown in sec

Figure 8 (b)

Figure 9

Current density for cathode oxide in A/cm$^2$