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New Insulator Film of Integrated Capacitor for a Silicon Strip Detector

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Abstract

New stacked thick insulator films have been developed to be applied for a silicon strip detector. We expected that the stacked films were superior integrated capacitors in terms of the high electric breakdown voltage, long-term reliability, large unit capacitance and radiation hardness. We measured the electrical behaviors of test capacitors with single-layer silicon dioxide (SiO_2), single-layer silicon nitride (Si_3N_4), NO (silicon Nitride – silicon diOxide), ON (silicon diOxide – silicon Nitride) and ONO (silicon diOxide – silicon Nitride – silicon diOxide) capacitors.

I. INTRODUCTION

The DSSDs (Double-sided Silicon Strip Detectors) for the KEK B-factory [1] employ an integrated capacitor in order to get away from saturation for a preamplifier which should be isolated from the d.c. bias of the detector. The bias voltage for obtaining a full depletion in the detector is approximately 100V. The capacitor is stressed in a part or all of the bias voltage. The integrated capacitor should meet following requirements:

- The breakdown voltage should be sufficiently high.
- The TDDDB (Time Dependent Dielectric Breakdown) property should be sufficiently long for using a long-time operation of silicon strip detectors.
- The leakage current through the insulator should be sufficiently small.
- In order to obtain a large charge collection efficiency, the capacitance is as large as possible compared to the inter-strip capacitance or the pn-junction capacitance.

In order to satisfy these conditions, a stacked insulator film, ON, NO or ONO insulator film [2][3], was chosen for an integrated capacitor. Since the dielectric constant of Si_3N_4 (7.4) is larger than that of SiO_2 (3.9), the capacitance of Si_3N_4 is larger than that of SiO_2 . The leakage current in Si_3N_4 is generally said to be larger than SiO_2 . In order

to include the advantages of each, we made stacked insulators. The stacked insulators are expected to have superior properties: a high breakdown voltage, long-term reliability, large unit capacitance and radiation hardness. A SiO_2 insulator and a Si_3N_4 insulator have different current transport mechanisms; the current in the SiO_2 flows by Fowler—Nordheim emission [4][5] and the current in the Si_3N_4 flows by Poole—Frenkel emission [6]. The Fowler—Nordheim emission is according to electron tunneling through the SiO_2 and the Poole—Frenkel emission is dominated by the so-called internal Schottky emission in the Si_3N_4 . Since the SiO_2 insulator limits injected electrons from the electrode to the Si_3N_4 insulator, we can expect less leakage current using the stacked insulator. The stacked insulator using different materials compensates for any weak spots of each other. The technology of the stacked insulators has been studied for only thin films which are used for VLSI DRAM and EEPROM devices so far, but have not been studied for thick films ($200\text{\AA} \sim 2000\text{\AA}$). Since traps on the interface between SiO_2 and Si_3N_4 work as recombination centers for radiation-originated carriers, the structure of stacked layers of SiO_2 and Si_3N_4 has a good chance to obtaining properties of radiation hardness; however, the radiation hardness properties are not discussed.

In section II we describe the fabrication procedures of the test samples. In section III we explain the experimental procedures and their results and then consider the results. In section IV we conclude the results and discuss future study plans.

II. FABRICATION OF TEST ELEMENTS

In order to neglect the voltage drop through a silicon substrate, we used silicon substrates which had bulk resistivity of $5 \sim 7\Omega \cdot \text{cm}$. The silicon substrate was n -type silicon, $525\mu\text{m}$ thick, $\langle 100 \rangle$ oriented and polished to a mirror finish. The SiO_2 on the substrate and the SiO_2 on the Si_3N_4 are called bottom SiO_2 and top SiO_2 , respectively. Figure 1 shows the structure of a capacitor using ONO insulator, which is three layers of stacked dielectric material, bottom SiO_2 , Si_3N_4 and top SiO_2 .

Figure 1: Structure of a capacitor using the ONO insulator.

The typical thicknesses of insulators were measured by process technicians using an ellipsometer. Two kinds of thicknesses of the bottom SiO₂ were made by a thermally grown process from the silicon substrate. The thickness of the bottom SiO₂, which was thermally grown at 1000°C in dry O₂ for 35min (in wet O₂ for 30min), was 440Å ± 1.1Å (1630Å ± 3Å). Top SiO₂ was also made by two methods: thermal SiO₂ and HTO (High Temperature Oxide by CVD*). The thermal SiO₂ was made by thermal growth at 1000°C in wet O₂ for 72min on Si₃N₄. This condition was equivalent to forming SiO₂ of 4360Å ± 8Å on a silicon substrate, which was a part of a process monitor element. We could not measure the thickness of the thermal SiO₂ upon Si₃N₄. We could estimate that its thickness was extremely thinner than 20Å, since no differences in the capacitance were observed between an ONO capacitor with top SiO₂ of thermal SiO₂ and an ON capacitor without top SiO₂. The HTO was made of SiO₂ deposition by the process of reaction of dichlorosilan (SiH₂Cl₂) at a gas flow rate 50sccm† and nitrous oxide (N₂O) with 500sccm at a temperature of 850°C and a pressure of 60Pa for 4min 25sec. The thickness of the HTO for the top SiO₂ was 100Å ± 2Å. The thicknesses of Si₃N₄ insulators were 390Å ± 3Å and 1640Å ± 11Å by the process of reacting dichlorosilan at a gas flow rate of 70sccm and ammonia (NH₃) with 700sccm at a temperature of 740°C at a pressure of 95Pa for 13min and 44min, respectively. This process is called LPCVD (Low Pressure Chemical Vapor Deposition). Table 1 lists the configuration of test capacitors. We prepared two samples of single-layer SiO₂, two samples of single-layer Si₃N₄, one sample of an ON stacked insulator, one sample of a NO(Thermal) stacked insulator and two samples of an ONO stacked insulator. After the insulators were made on the substrate, polysilicon was deposited on the insulator to define the capacitor area and on

*CVD stands for Chemical Vapor Deposition

† sccm stands for Standard Cubic Centimeters per Minutes.

Table 1: Table of test samples.

	bottom SiO ₂	Si ₃ N ₄	top SiO ₂
SiO ₂	440Å	—	—
	1630Å	—	—
Si ₃ N ₄	—	390Å	—
	—	1640Å	—
ON	440Å	1640Å	—
NO(Thermal)	440Å	1640Å	< 20Å
ONO(Thermal)	440Å	1640Å	< 20Å
ONO(HTO)	440Å	1640Å	100Å

Thermal means to be covered with the top SiO₂ of the thermal SiO₂ on the Si₃N₄. HTO is covered with the top SiO₂ of the HTO.

the backside of the substrate to provide a backside contact. The polysilicon was doped by phosphorus. The patterns of the capacitors were formed by standard photoresist techniques. The capacitors were shaped as circular disk with radii of 125, 250, 500 and 1004μm.

III. EXPERIMENTS AND DISCUSSION

All measurements were made at room temperature. Figure 2 shows a schematic diagram of the setup for the electrical measurements.

Figure 2: Experimental setup.
DUT stands for Device Under Test.

A. Capacitance

Capacitance measurements for the capacitors were made using a HP4194A Impedance/Gain-Phase Analyzer. The measurement frequency was 10kHz and the amplitude for the a.c. frequency was 500mV. We determined the unit capacitance by taking an average over four capacitors ($r = 125\mu\text{m}$ to $1004\mu\text{m}$). The measurement accuracy was about $\pm 2nF/cm^2$.

Figure 3 shows the unit capacitance of the capacitors using the SiO₂, Si₃N₄ and ONO(Thermal) insulators. The solid, dotted and dashed lines are the theoretical values

Figure 3: Unit Capacitance of single-layer SiO_2 , single-layer Si_3N_4 and ONO(Thermal).

for the unit capacitances of the ONO(Thermal), the SiO_2 and the Si_3N_4 , respectively. The measured capacitances were consistent with the thicknesses measured with an ellipsometer.

The unit capacitance of the ONO(Thermal) was approximately 1.7-times larger than the capacitance of single-layer SiO_2 . The unit capacitance depended only on the thickness and the combination ratio of SiO_2 and Si_3N_4 .

B. Current Transport

We applied bias voltages and measured the current with a Keithley Model 237 high voltage source measure unit. A positive voltage was applied from a polysilicon gate electrode on an insulator. Since we used n -type silicon substrate, current does not flow in an insulator for a negative bias voltage due to the development of a depletion region in the silicon substrate. We, therefore, could observe electron injection from the silicon substrate and/or hole injection from the polysilicon gate electrode. The applied voltages were swept with a step of about 0.5 MV/cm on the average electric field. The average electric field was derived from the applied voltage divided by the total geometrical thickness of the insulators. Since we filled up the traps in the insulators for each voltage step, it took $100 \sim 20000 \text{ sec}$ before the current reached a steady state condition, i.e. $\frac{\Delta I}{I} \leq 0.05\%/ \text{sec}$, or the current decreased below the measurement limit, i.e. $I \leq 10^{-13} \text{ A}$.

Table 2 shows the electric breakdown properties for an

Table 2: Breakdown properties.

	Electric field (MV/cm)		Electric flux density	
	$\bar{E}$	SiO_2	Si_3N_4	(coulomb/cm^2)
$\text{SiO}_2(1630\text{\AA})$	7.5	7.5	—	2.6×10^{-6}
$\text{Si}_3\text{N}_4(1640\text{\AA})$	8.0	—	8.0	5.2×10^{-6}
ON	9.0	14.4	7.6	5.0×10^{-6}
NO(Thermal)	8.9	16.7	8.8	5.8×10^{-6}
ONO(Thermal)	8.0	12.8	6.7	4.4×10^{-6}
ONO(HTO)	8.0	12.5	6.6	4.3×10^{-6}

$\bar{E}$ means the average electric field.

average electric field ($\bar{E}$), electric field on SiO_2 , electric field on Si_3N_4 and electric flux density. The electric flux density was estimated from the applied voltage, the geometrical thicknesses of the insulators and each dielectric constant, where we assumed no charge in the insulators and on the interface of the insulators. The breakdown properties included the effect of TDDB, since the stress time was very long, approximately over one day from the start of the sweep before a breakdown. The single-layer SiO_2 had the smallest breakdown property for both $\bar{E}$ and the electric flux density. The NO(Thermal) had the highest breakdown property for the electric flux density. We have traditionally used typically a $2000\text{\AA}$ SiO_2 insulator for the readout capacitor. When a voltage of 100 V was applied to the $2000\text{\AA}$ SiO_2 insulator, the electric field on it was 5 MV/cm . All test samples satisfied the minimum requirement of the electric breakdown voltage.

Figure 4 shows the current density versus the electric flux density of the SiO_2 , Si_3N_4 , ON, NO(Thermal), ONO(Thermal) and ONO(HTO). The lower limit of the measurement was approximately 10^{-10} A/cm^2 . At the last point of the plots, the insulators were broken. In order to discuss the performance of the insulator, i.e. low leakage current, high breakdown property and large unit capacitance, we chose the electric flux density for the lateral axis. This is because a larger electric flux density shows a larger unit capacitance and higher electric breakdown property. A good insulator, therefore, shows a lower current density and a higher electric flux density for breakdown.

The area of a readout capacitor on a silicon strip detector is typically $3.25 \times 10^{-3} \text{ cm}^2/\text{strip}$. In order to obtain a low noise level, we demand that the leakage current in the insulator is under $1 \text{ nA}/\text{strip}$, i.e. $0.3 \mu\text{A}/\text{cm}^2$. The single-layer SiO_2 was the lowest electric flux density for breakdown and the highest current density. On the other hand, the NO(Thermal) insulator showed the highest electric flux density for breakdown and the least current density. The single-layer Si_3N_4 showed the secondly highest electric flux density for breakdown and the second least current density. The ONO(Thermal), ONO(HTO) and ON insulator showed almost the same property as each other.

The difference between the Si_3N_4 and NO(Thermal) is the existence or nonexistence of top SiO_2 . The top SiO_2

Figure 4: Current density versus electric flux density

plays the role of a barrier for holes from the polysilicon electrode.

When we made the Si_3N_4 layer onto the silicon substrate, we could assume that the surface of silicon was oxidized with thin natural SiO_2 , which played the role of bottom SiO_2 . We recognized that the single-layer Si_3N_4 actually consisted of natural SiO_2 and Si_3N_4 in that order. The NO(Thermal) also accompanies natural SiO_2 between silicon and Si_3N_4 . We can separate the data into two groups in terms of the thickness of the bottom insulator. One group has thin natural SiO_2 ; another group has 440Å SiO_2 . The two groups property were clearly different. If electrons are injected into thick SiO_2 , the injected electrons are accelerated by the electric field for a long distance. The thicker SiO_2 provides more energy for electrons. In thinner SiO_2 , electrons have less energy. In thick SiO_2 , the electrons have a good chance to excite another electron in the valence band to the conduction band. Thinner bottom SiO_2 , therefore, flows a smaller current transport. If we inject electrons from a polysilicon electrode, the top SiO_2 probably decreases the current transport effectively.

IV. SUMMARY

This article provides the first data for thick stacked insulators, single-layer SiO_2 and single-layer Si_3N_4 . We

evaluated these insulators in terms of the capacitance and current transport. The unit capacitance of the ONO(Thermal) was approximately 1.7-times larger than the capacitance of single-layer SiO_2 . The unit capacitance depended on the thickness and the combination ratio of SiO_2 and Si_3N_4 . We understood that the thinner SiO_2 layer on the side of electron injection passed less current. We found that the stacked insulator was more useful than thick single-layer SiO_2 . We can temporarily conclude that the most useful insulator is the NO(Thermal) type, which is covered with a thin SiO_2 on both sides of Si_3N_4 .

In a further study we will investigate the effect of the SiO_2 thickness dependence on Si_3N_4 for injected electrons. We will evaluate the side effect of the thermal oxidizing process on the pn -junction properties. The TDDb property will be checked, since we will use the detector for a long time. Radiation hardness will also be tested, since the detectors will be used under a radiation environment.

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