ABSTRACT

A ultra wideband RF-MEMS shunt switch with a PZT/HfO2 stacked insulator has been developed for microwave and millimeter wave applications.

The both of the conjunctive dielectric constant $80$, of PZT($\varepsilon_r=800$)/HfO2($\varepsilon_r=20$)stack layer and a $M$-match circuit contribute to high isolation of $-30$dB at ultra wideband from $1$GHZ to $50$ GHZ frequencies. The increase of the trap density in the HfO2 layer caused from carrier injection from the electrode of the switch into the insulator is smaller than that of silicon nitride(Si3N4) under constant voltage stress, resulting in the suppression of the stiction of the switch. The percolation and annealing model is analytically introduced to explain the lower trap density and higher stress-endurance characteristics of HfO2 than Si3N4 usually used as switch insulator. The projected lifetime of the switch with the stacked layer is more than 10 years. This is the best data ever reported.

1. INTRODUCTION

The RF-MEMS switches have been focused on its good RF characteristics of high isolation and low insertion loss for several years. RF-MEMS switches are expected to find their new field of ultra wideband RF front-end networks for beam steering, signal routing, transmit/receive isolation[1] and short range ultra wideband switched-filter applications presented by FCC.

The shunt-type switch has charge injection from the electrode into the insulator, causing stiction of the switch.

In the present paper, the shunt-type RF-MEMS switch has been developed with PZT/HfO2 stacked insulator instead of silicon nitride for wideband applications and high reliability.

2. WIDEBAND SWITCH DESIGN AND FABRICATION

The two wideband methodologies are introduced to obtain a wideband switch from $1$GHZ to $50$GHZ frequencies; one is $M$-match circuit, another is higher down-state capacitance. The designed wideband switch structure is shown in Fig.1. The HfO2(45nm)/PZT(230nm) stacked layer is introduced as the switch insulator(Fig1), the former is for high reliability performance and the latter for higher capacitance. The conjunctive dielectric constant of PZT($\varepsilon_r=800$)/HfO2 ($\varepsilon_r=20$)stack layer is $80$, resulting in wideband isolation characteristics around the resonant frequency in the present work. The length of the high impedance transmission line of $M$-match circuit between two

![Fig.1 RF-MEMS shunt switch with HfO2/PZT:stack layer](image1)

![Fig.2 S-Parameter measurements for RF-MEMS switch with PZT/HfO2 stacked layer. Dotted line: show the simulation by Sonnet](image2)
bridges is 800 Ωm estimated from Sonnet simulator.

3. RF CHARACTERISTICS OF THE SWITCH

The measured insertion loss and isolation are shown in Fig.2. The insertion loss is less than 0.4dB at 50GHz. The isolation is higher than 30dB from 1GHz to 50GHz. The simulated results by Sonnet well coincide with measured data. These characteristics are sufficient for wideband operation at microwave and sub-millimeter frequencies in many cases.

4. THE ANALYSIS OF CARRIER TRANSPORT

4.1 Initial I-V characteristics of the HfO₂/ PZT and Si₃N₄ layers

The M(Metal)-I(Insulator)-M(Metal) structure (P₂000 m) is introduced to analyze the carrier injection and carrier transport mechanism of the switch. The leakage current of the MIM structure is shown as a function of applied voltages, comparing that of Si₃N₄ in Fig.3. The figure shows the two humps observed in the HfO₂/PZT stacked layer, contrasting to no humps in the Si₃N₄ and shows 3 orders magnitude smaller leakage current of HfO₂/PZT than that of Si₃N₄, indicating the lower trap density of the HfO₂/PZT than that of Si₃N₄ for stress-free samples.

4.2 Constant voltage stress test of MIM for carrier transport analysis and evaluation of the switch reliability

The continuous constant voltage stress tests of the MIM capacitors (P = 200 m) consisting of the HfO₂/ PZT stacked layers are adopted to evaluate the reliability of the wide band switch of the present work. Usually a switch reliability was confirmed by operating the switch using 100KHZ on-off signal. But in this case, a part of charges injected into the dielectric are come in and out the insulator with applied frequency. Consequently, the charging effect into the insulator are moderated and occurrence of the stiction of the switch sometimes suppressed.

So the continuous constant voltage stress is more severe and realistic condition to evaluate the life time of the present switch more accurately.

![Graph showing leakage current vs. applied voltage before constant voltage stress for MIM structure](image)

The constant stress voltage of 20V (1/2 breakdown voltage and the switch actuation voltage) is applied for HfO₂(45nm)/PZT(230nm) dual layer before breakdown of the stack occurs as shown in Fig. 4.

After constant leakage current of e-11A flows for initial a few minutes, the leakage current drastically decreased to one order smaller than the initial value and reached the minimum value in about fifteen minutes. Moreover leakage current increased with some vibrations in a few minutes intervals, resulting in leakage current level of e-9 but not even at breakdown of the stack (Fig.4). The step current or burst current, namely random telegraph leakage current of the HfO₂/PZT stack, happen to occur with small amplitude for a few ten seconds and diminish instantly as shown Fig.6.

As for the silicon nitride of the switch insulator, the leakage current vibrations occur in only a initial stage of the stress time, in less than 10 minutes (Fig.5).
The initial current level is very high like e-7A, four orders larger than that of the PZT/HfO2 stack.

After the unstable initial stage, the leakage current of the Si3N4 increases monotonically until breakdown.

4.3 The carrier transport model applied for both the HfO2/PZT stack and Si3N4

The model is presented schematically in Fig7,8. As for carrier transport analysis of the stacked layers, such as PZT/HfO2 in the present case, current continuity principle is conveniently applied for dual layer[2]. So PZT/HfO2 stack are simplified to HfO2 single layer by applying the principle(Fig.7).

Basically the leakage current flows when injected electrons into the insulator from one of the electrode hop between trap centers and conduction band and reach the another electrode(Fig.9).

By applying the high electric field of the stress voltage, local heating effect suppresses the generation of new trap centers and partially anneal out the old centers, likely annealing effect, resulting in diminishing the percolation path(Fig.7,9) and the current hump appearing (Fig3).

The step current comes from newly developed trap centers by high electric field, resulting in the additive generation of the percolation path (Fig7).
Comparing the PZT/HfO stack and Si3N4, the HfO2 / PZT stack has smaller initial trap density (Fig.3) and has larger endurance for high electric field generation of the trap centers and larger annealing effects than silicon nitride under the constant stress voltage(Fig.4,5).

5. HIGH RELIABILITY RF-MEMS SHUNT SWITCHES

The reliability of the RF-MEMS shunt switch is estimated from a capacitance leakage current under the constant voltage stress, corresponding to $e_{12}$ trap density, where the stiction starts to occur[3]. Therefore, if the life time projected from capacitance leakage current is 10 years, then life time of the real switch is over 10 years.

The times where leakage current reached the current level, corresponding to $e_{12}$ trap density, are plotted as a function of the constant stress voltage on the PZT/HfO2 stack and silicon nitride insulator in Fig. 10.

From the Fig.10, almost 10 years lifetime of the PZT/HfO2 stacked switch is projected at around 10V of actuation voltage, even now under tests. On the other hand, that of the silicon nitride is very small.

Fig.10  Lifetime projection from constant voltage stress test

6. CONCLUSION

The RF-MEMS shunt switch with a newly developed insulator of the PZT/HfO2 stack has extremely wideband characteristics and high reliability. These come from large dielectric constant of the PZT and small leakage current of the HfO2 under constant voltage stress for a long time. The longer lifetime of the PZT/HfO2 stacked switch is projected to over 10 years than that of the switch with the silicon nitride.

REFERENCES

