RF MEMS Sensitivity to Radiations

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***Abstract* — Silicon dioxide and silicon nitride as well as other insulating materials are used in micro-electro-mechanical systems. However, their tendency for electrostatic charging diminishes the device reliability. The charging effect becomes significant when these devices are subjected to ionizing radiation. The irradiation induced defects and charging depend on the nature of irradiation, the underlying metal layers and the metal-insulator interface properties. The sensitivity of RF micro-electromechanical systems to ionizing radiation is presented taking into account experimental data and the simulation of charge generation and induced damage.**

I. Introduction

The extremely high insulation resistance and breakdown field strength of SiO_2 and Si_3N_4 as well as their technological compatibility make them preferred materials for insulation in microsystem technologies. In the field of micromechanics, especially as part of electrostatically driven actuators and variable capacitor devices, such layers protect against short-circuit caused by contact of the movable parts across the electrode area. These micromechanical systems (MEMS) receive increasing interest for space technology and for a large variety of more or less hostile terrestrial applications. A particular area in space application is in picosats [1], where the radiation shield is minimal in order to reduce the satellite mass. Depending on the material properties and environmental conditions, the surface of a dielectric can be capable of localized charge storage for a considerable time. In addition these materials are characterized by a very low mobility of surface charges. Furthermore, SiO_2 and Si_3N_4 provide trap sites for positive and negative charges both deep in volume and at interfaces of multi-layer stacks. The parasitic charges come into the dielectrics of a MEMS device uncontrollably during handling, operation and mainly when they are stored or operate in a radiation rich environment.

To date, few radiation tests have been performed on MEMS devices. The tests on MEMS accelerometers have shown the technology proneness to radiation effects at moderate dose levels [2-5]. The reported radiation effects were attributed to electrostatic force caused by charge accumulation in SiO_2 and/or Si_3N_4 dielectric layers. Furthermore, a quantitative model for the electrostatic force was developed for some mechanical structures [4]. On the other hand, no investigation has been performed in view of the in depth distribution of the generated charges and defects.

The effect of ionizing radiation induced charging in insulators has attracted serious attention in applications of X-ray spectroscopy [6], scanning electron microscopy [7], ion implantation, etc. These investigations were primary focussed on the secondary electron emission and the resulting insulator charging. These specific applications restricted the investigations to low X-ray photon energies (≤30KeV), where the Auger and photoelectric effects dominate. Furthermore, due to low photon energies the issue of defect generation was related to migration due to material charging.

The aim of the present work is to combine the already available scattered information with recently performed simulations on both electromagnetic and particle ionizing radiation in order to obtain a better understanding of charging effects RF MEMS, hence to get a more clear image on their sensitivity to radiation. The results interpretation is based on the layer composition and structure as well as the defect and recoiled atom distribution.

II. Charging Mechanisms

The mathematical analysis, which has been used to calculate the effect of irradiation charging in MEMS accelerometers [4], RF switches [5] and capacitive MEMS [8] was based on the calculation of one quantity (force or charge) derived from the other. This analysis did not calculate either quantity from knowledge of environmental conditions, i.e. it did not explain how the dielectric charge is created in the first place. Credible candidates for charging mechanisms have been suggested by Lee et al. [3] who investigated the effect of proton and electron (from SEM) irradiation in sensor-only. The negative charging of dielectrics, when they are subjected to electron radiation at energies greater than 10KeV, was empirically known, experimentally demonstrated in MEMS accelerometers [3,4] and later simulated [9] for scaning electron microscopy applications.

The effect of actuation voltage increase in RF MEMS switches due to dielectric charging by secondary electron emission from the insulating layer was demonstrated in [5]. There the devices were irradiated with Co^{60} gamma-rays under positive or negative (reverse) bias. The effect of gamma-rays induced charging in MEMS optical mirrors with PZT dielectric layer was demonstrated in [10].

In the case of ion radiation, the positive charging of dielectric layers was demonstrated in [2,3] by sensor-only proton irradiation. The positive charging was interpreted on the basis of the domination of secondary electron emission over the backscattered electron absorption. Finally, the ion-beam irradiation induced electric potential on the surface of an insulator, due to electric charge buidup, was investigated in [11]. By monitoring the He ion scattering, it was found that the surface potential was possitive, result being in good agreement with [2,3]. In [11] and for the case of SiO_2, using 2.4MeV He^{2+} ions, the surface potential was found to rise up to 66.2kV for non-coated 3mm thick samples.

In view of the limited literature on ionizing radiation charge generation in insulating materials, we are led to the conclusion that the better understanding of radiation effects in RF MEMS require further investigation of the charge generation mechanisms. In the following, the issue of charge generation is trated separatelly for photon and ion radiation.

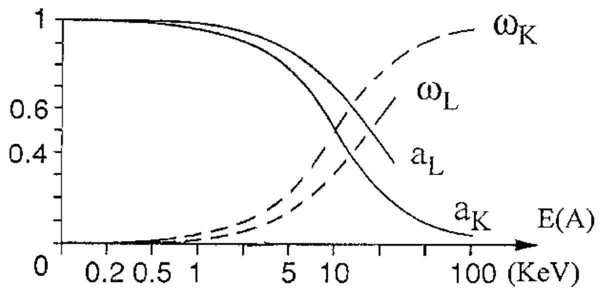

Fig. 1. Change of the fluorescence yield, ω, and the Auger yield, α, as a function of the binding energy E(A) [$E_A(K)>E_A(L)$] of an excited photoelectron (figure reproduced from [6]).

A. Electromagnetic ionizing radiation

The investigation of ionizing electromagnetic radiation effects includes photon energies ranging from a few tens of kiloelectronvolts (20KeV) that corresponds to soft X-ray source emission up to 1MeV that corresponds to a Co^{60} gamma-ray source. This wide photon energy range allows us to almost distinguish the contribution of three basic energy loss mechanisms. The Auger and photoelectric effect are the dominant mechanisms for the absorption of X-rays while the Compton effect occurs at high photon energies and may lead to defects creation through the high energy Compton electron [12].

The absorption of soft X-rays gives rise to ejection of a photoelectron from an excited atom. A de-excitation process that is characterized by a photon emission (fluorescence effect) or an Auger electron emission follows this ejection (fig.1). The initial photoelectron and nearly one or more Auger electron are emitted quite simultaneously from an excited atom. These electrons propagate in the material where they interact with other atoms. The inelastic interactions with valence electrons give rise to electron hole pair creation (fig.2). Furthermore, when these electrons are generated close to the surface, at a distance less than the escape length s, they may escape into vacuum or in the substrate on which the insulating layer has been deposited, leaving a positively charged insulator layer.

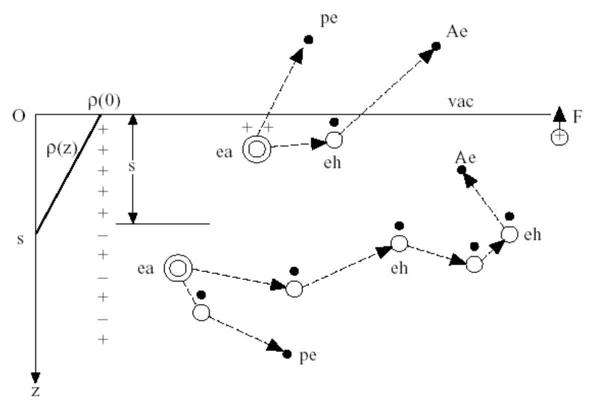

Fig.2. Sketch of the atomic mechanisms induced by the photoabsorption effect. Photoelectrons (pe) and Auger electrons (Ae) are issued from an excited atom (ea). These electrons generate electron-hole pairs during their transport. Close to the surface excited atoms (z<s) lead to secondary electron emission and the material is positively charged (figure partially reproduced from [6]).

The thickness of this positively charged layer corresponds approximately to [11]

$$s\left(\overset{o}{A}\right) \approx \left[E_{ki}^{7/4} - E_{kf}^{7/4}\right] / E_p^2 \qquad (1)$$

where E_p is the free plasmon energy, E_{ki} and E_{kf} are the electron initial and final kinetic energies, respectively. Here it must be pointed that the escape length has fixed values for the Auger electrons, depending on the de-excitation processes. For the photoelectrons, the escape length depends on the energy of the absorbed photon. In RF MEMS the dielectric layer is deposited on a conducting one. Since the described process does not depend on the irradiated material conductivity, upon irradiation there will be a simultaneous process of secondary electron emission from the insulator towards vacuum and the metal substrate. Simultaneously, secondary electrons will be emitted from the metal substrate towards the insulator layer. Thus, the sign and the distribution of the insulator charge will be determined by the rates of the secondary electrons emitted from the substrate and the ones emitted into vacuum and substrate. Therefore, the net charge of a bare insulating layer, irradiated with X-rays or gamma rays, is expected to be positive.

As already mentioned, the aim of the present work is to obtain a clearer image on the sensitivity of RF MEMS to ionizing radiation. For this reason we simulated the effect of ionizing electromagnetic radiation on a simple structure consisting of a insulating layer on a metal film that in turn has been deposited on a glass substrate. This structure resembles a varactor and a RF switch in the OFF position, or even in the ON position if we bear in mind that there is always an air gap between the metal bridge and the insulator surface. For the latter, the applied bias may assist to the collection of the secondary emitted electrons or diminish this process by repelling the emitted electrons, as demonstrated in [5]. The structure used in the simulation procedure is presented in Table I.

Table I. Simulated layer structure

Composition	Thickness (nm)
SiO_2 or Si_3N_4 or HfO_2	100
Au	200
Cr	20
Glass	-

Three different insulators were used for the ionizing radiation simulation. The materials choice was based on their use in RF MEMS and electrical characteristics. The simulation was performed with the MCNP code, which allowed the division of the insulating layer in five cells with thickness of 20nm each one. The code was used for the calculation of charging under ionizing radiation with photons of 20KeV, 100KeV and 1MeV. The charge distribution for Si_3N_4 is presented in Fig.3

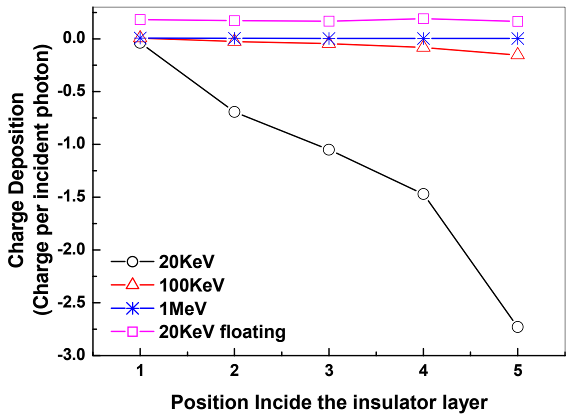

Fig. 3. Radiation induced charging in Si_3N_4

The simulation results clearly show the effect of charging from the secondary electron emission from the Si_3N_4 layer and the underlying Au film. At low photon energies the Auger yield is much higher than the photoelectron one. Thus the escape length is determined by the Auger electron emission. Due to small energies of Auger electrons the thickness of positively charged film is small and the material charge becomes negative due to the Auger electrons emitted at higher rates from the Au film, since it exhibits a much higher absorption to soft X-rays. This clearly justifies the accumulation of negative charge close to the Au interface. The electron supply from the Au film is also confirmed by applying the same simulation to a bare (floating) Si_3N_4 film. In this case the simulation leads to a uniform positive charge distribution across the insulator (fig.3). Increasing the photon energy to 100KeV and finally to 1MeV, we increase in fact the emission of photoelectrons which in turn leads to an increase of escape length. For high photon energies Compton electron are generated with energies of the order of several hundred KeV [12]. The high-energy photoelectrons and Compton electrons are emitted throughout insulator volume. Moreover, Compton electrons emerge from Au layer into insulator layer, loose energy through ionizing interactions and due to their high energy they are emitted as secondary electrons from the insulator. This ionizing process increases further the insulator positive charge. The absorption coefficient decreases drastically when the photon energy increases. This leads to a decrease of the deposited charge, the insulator-vacuum surface becomes positive while the insulator-Au one negative. At 1MeV photon energies the insulator becomes positive with a charge distribution that decreases close to Au interface.

The SiO_2 was found to behave in a similar way to Si_3N_4. In contrast the HfO_2 insulating layer exhibited a completely different behavior (fig.4).

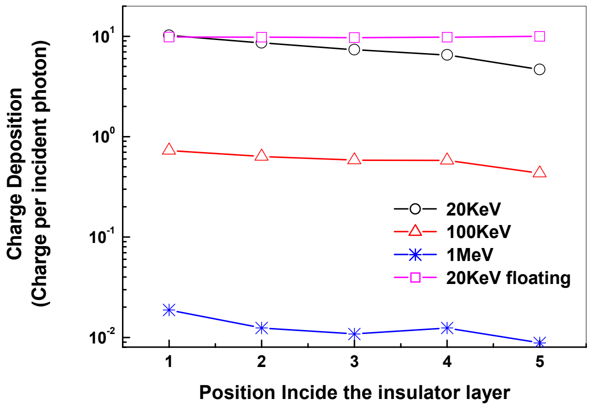

Fig. 4. Radiation induced charging in HfO_2

In this insulating material the charge was found to be positive for all photon energies. The distribution shows a small decrease towards the Au film interface, due to photoelectron and Auger electron emission from Au film, and the net charge decreases with the photon energy increase. The supply of electrons from Au layer is confirmed by applying the simulation to a bare (floating) HfO_2 layer (fig.4), which show a uniform distribution. The behavior positive charging for all simulated photon energies may be attributed to the large atomic number of Hf (72) and its small difference with respect to that of Au (79).

B. Ion irradiation

In the present work, the investigation of charging due to ion radiation was restricted to 1MeV protons. In order to understand the proton radiation effects we must bear in mind that the proton energy loss is carried out through displacement damage and ionization. The displacement damage is carried out primary by protons leading to atom removal from their lattice sites. The energy transferred to the recoiled atoms is large enough allowing them to behave as secondary projectiles and to further generate vacancies and interstitial. These point defects may lead to the formation of more complex ones. Finally, both protons and recoiled atoms loose energy through ionization process and contribute to electron hole pair generation. Here it must be pointed that although the ionization leads to material charging, as already has been analyzed, the defect formation plays a significant role on the insulator charging. The charging is enhanced through carrier trapping in the generated defects throughout the insulator volume or at the interfaces through the Maxwell-Wagner-Sillars effect. The latter leads to the generation of large dipolar moments.

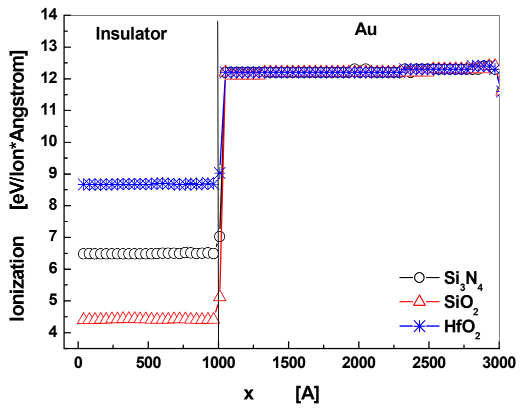

Fig.5 Ionization deposited energy by 1MeV proton radiation

The TRIM code has been employed for the simulation of ionization and damage. The TRIM code allows the calculation of the primary generated defects and charges due to both the incident ions and the recoiled atoms across all layers. The energy deposited for ionization per particle and unit length by the 1MeV proton irradiation is presented in Fig. 5.

On the first spot, the results on the ionization rate for SiO_2 and Si_3N_4 indicate a uniform ionization rate throughout the insulator layer. The results are in good agreement with the fact that the electron-hole pair generation energy in Si_3N_4 is lower, about 10.8eV, while in SiO_2 is higher, about 17eV. Taking into account these values, we are lead to the conclusion that more electron hole pairs are generated in Si_3N_4, which seems to be more vulnerable than SiO_2, to proton and as already shown [13] to alpha particle radiation [13]. This indicated that Si_3N_4 seems to be more prone to single event burnout than SiO_2. The case of HfO_2 needs further investigation. The vacancy distribution increases towards the Au interface. There, the defect concentration, originating from the pre-existing introduced during insulator deposition, and the radiation introduced ones increases significantly giving rise to charge trapping. The trapped charge will be larger at the back interface of the insulating layer. This charge will be partially neutralized by the metal image charge. It must be emphasized that this speculation needs further confirmation through dipolar relaxation measurements.

III. Conclusion

The sensitivity of RF MEMS insulators to electromagnetic and particle ionizing radiation has been presented. The insulator charging is conducted through secondary electron emission. Both the photon energy and the underlying substrate material properties play a significant role on the sign of the insulator net charge. Finally, for ion irradiation Si_3N_4 seems to be more vulnerable than SiO_2. The sensitivity of high-k materials to ionizing radiation needs further investigation.

Acknowledgement

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