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Using low energy electrons to neutralize electrostatic charges on cryogenic test mass mirrors of future gravitational wave detectors

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Summary. — Electrostatic charging is a limiting noise source for gravitational wave detection already at room temperature. The development of a mitigation method compliant with cryogenics is mandatory to preserve the performances envisaged by the upcoming generation of gravitational wave detectors. We have recently proposed the use of selected energy electrons (below few hundreds eV) impinging on the mirror surface to neutralize electrostatic charges of both polarities. Here we present the experimental evidence of the method on a 20 nm SiO_2/Si substrate.

1. – Introduction

To preserve the unquestionable improvements deriving by cooling down the mirrors at cryogenic temperature, methods adopted to mitigate all possible noise sources in the new generation of gravitational wave detectors need to be compliant with cryogenics. Among others, electrostatic charging on test masses has already been shown to be a limiting noise source [1]. The mitigation method proposed by the LIGO collaboration successfully works at room temperature. It consists in the mirrors' exposure to some tens of mTorr of N_2 plasma [2]. So as conceived, however, such a solution cannot be applied at cryogenic temperature, since the formation of a significantly thick condensed N_2 layer on the mirrors [3, 4] will severely affect the detection [5-7].

In our previous papers [8, 9], we have suggested an alternative method, compatible with cryogenics, to neutralize electrostatic charges on test masses. As schematically shown in fig. 1, the basic concept relies on the possibility to tailor electron energies to induce positive or negative charge on a neutral surface, depending on its Secondary Electron Yield (SEY or δ). SEY is an intrinsic material property, quantitatively defining the interaction with electrons. Once a beam of electrons (also called primary electrons) impinges on a surface, SEY is given by the ratio between the number of all emitted and

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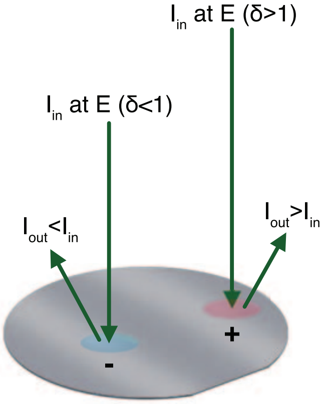

Fig. 1. – Schematic representation of charging by irradiating a neutral surface with electrons: if irradiation occurs within an energy range for which $\delta < 1$ (*i.e.*, $I_{out} < I_{in}$), a negative charge will be delivered on the surface (blue circle); if electron irradiation occurs within an energy range for which $\delta > 1$ (*i.e.*, $I_{out} > I_{in}$), a positive charge will be left on the surface (red circle). Figure adapted from [9].

the incident electrons. As extensively described elsewhere [8, 10-15], it is experimentally determined as SEY=I_{out}/I_{in}, where I_{in} is the current of the primary electron beam and I_{out} is the electron current emerging from the surface. Depending on the impinging electron energy E, δ can be greater, lower or equal to 1. This means that, by properly choosing the primary electron energy irradiation, we can remove (irradiating at E where $\delta > 1$) or add (at E where $\delta < 1$) electrons from/to a neutral or charged surface or part of it.

Such a neutralization strategy, based on electron irradiation, has been proved in its basic aspects [8, 9]. Here we present the experimental evidence of the method. By performing electrostatic measurements on a 20 nm SiO_2/Si prototypical substrate, we show how to neutralize an electrostatic charge (both positive and negative) by properly tuning the impinging electron energy on the sample surface. A study of irradiation parameters is given, highlighting the strict correlation between the surface voltage, monitored during the neutralization process, and the intrinsic SEY properties of the material.

2. – Experimental details

Experiments are performed in an ultra high vacuum (UHV, base pressure $\sim 1 \times 10^{-10}$ mbar) μ-metal chamber at the Material Surface Science Laboratory of the INF-LNF (Frascati, Italy). As representative of the mirror coating, we have considered a $8 \times 8\,\text{mm}^2$ sample of a commercial wafer, composed of 20 nm of stoichiometric SiO_2 thermally grown on p-boron doped Si substrate (IHP Microelectronics). Details on SEY measurements are reported in [8]. Charging and neutralization experiments are done irradiating the electrically insulated sample with a Kimball Physics electron gun (equipped with a standard Ta disc cathode) at different energies. During irradiation, an incident current of the order of tenth of nA on a sample area of $\sim 1\,\text{mm}^2$ is maintained. Voltage induced on the sample surface is measured with a non-contact electrostatic voltmeter (ESV 1000) positioned outside the UHV chamber. The electrostatic voltmeter measures the voltage of the image charge induced on a metallic plate connected to the irradiated

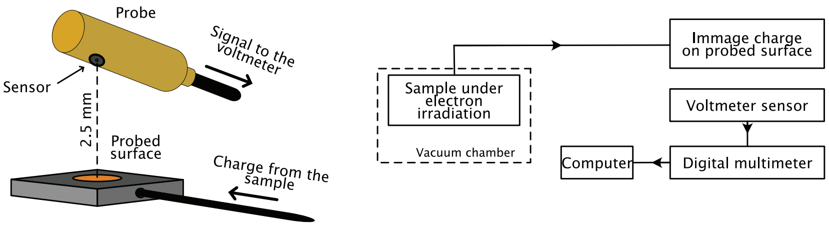

Fig. 2. – Right: electrostatic voltmeter set-up. The sample is connected to a metallic plate (Probed surface). Under electron irradiation, a sample's image charge is induced on the Probed surface. The voltage generated by such a charge is revealed by the voltmeter sensor and acquired by a digital multimeter. Left: data acquisition scheme for voltage measurements.

sample. The voltage revealed by the voltmeter sensor is acquired by a digital multimeter (HP34401A) with a resolution of the order of tens of mV. A sketch of the electrostatic voltmeter set-up and the data acquisition scheme are reported in fig. 2.

3. – Results

Figure 3 shows an example of charging/neutralization by electron irradiation, performed by considering the SEY characteristics of the sample showed in (a). Charging measurements are here reported for the specific case of an initially neutral sample. However, the charging behavior is general whatever the initial surface voltage V$_s$. Let us consider each case in detail.

Figure 3(b). Positive charging: irradiation is done with electron energy $E_1 = 400\,\mathrm{eV}$; at this energy $\delta > 1$. The surface will start to positively charging, continuously attracting both the impinging electrons and part of the low energy emitted ones. Emitted electrons, in facts, have an energy distribution between 0 and E_1 and the large part of them has a very low energy (below ∼50 eV) [10]. This process leads to reach a stable surface potential V_s which will depend on SEY at that specific impinging electron energy (data not reported here).

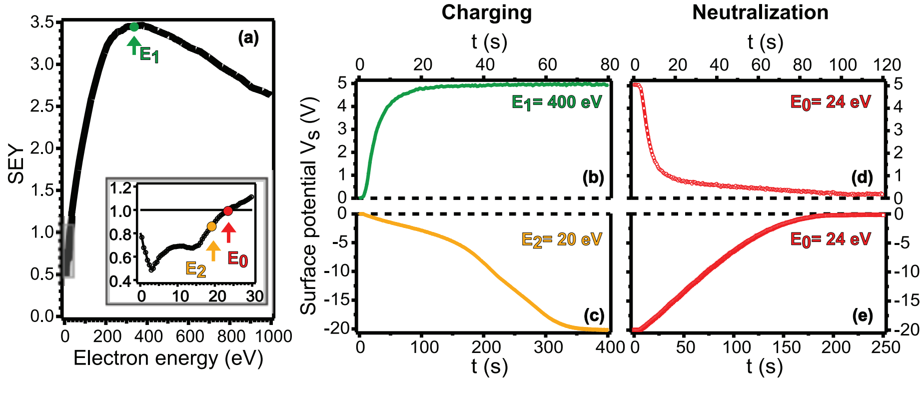

Fig. 3. – (a) SEY curve of 20 nm SiO$_2$/Si sample. The inset is a magnification of the low energy region. Arrows point to the δ values at the charging/neutralization irradiation energies. Charging measurements to positive (b) and negative (c) voltage. Neutralization starting from positive (d) and negative (e) voltage.

Figure 3(c). Negative charging: irradiation is done with electron energy $E_2 = 20\,\text{eV}$; at this energy $\delta < 1$. Electrons will be deposited on the surface, inducing an increasingly negative surface charge. Such a negative charge will act as a retarding potential for further incoming electrons. These will continue to be deposided until their effective energy (that is, the energy they have considering the retarding field) is not enough to overcome V_s. A stable condition is reached.

Figure 3(d) and (e). Neutralization: whatever the initial V_s, irradiating the surface with electrons at $E_0 = E(\delta = 1)$ charging neutralization will occur. This can be easily deduced also by looking the schematic representation in fig. 1, considering $I_{in} = I_{out}$.

4. – Conclusion and perspectives

Going further the proof of concept recently proposed [8], here we have reported the experimental validation of a possible method to mitigate charging on test masses of gravitational wave detectors. We have shown that low energy electron irradiation does neutralize both positive and negative charges on a surface by properly tuning the electron energy. In particular, there is a strict correlation between neutralization parameters and SEY. This strongly suggests that, by studying SEY features of any specific coating, it is always possible to extract operational parameters to discharge it.

More investigation are needed, also on other possible materials, to evaluate the effects of electron irradiation (below few hundreds eV) in inducing defects on the material structure. However, minimal effects on mirror quality are expected due to the low mean free path of low energy electrons below the surface ($\sim 1\,\text{nm}$ between 10 and $1000\,\text{eV}$ [10,12]).

Electron irradiation is compatible with cryogenics and will work at room temperature as well. As an added value at cryogenic temperature, it is known that electrons efficiently induce molecular ice non-thermal desorption [4,16]. Work is in progress to find the right parameters to combine frost and charge mitigation. Further study will come.

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