

HIGH EFFICIENT, LOW COST ELECTRET CHARGING SET-UP FOR MEMS BASED ENERGY HARVESTING SYSTEMS

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Abstract: A new type of charging electrets is presented. Low cost equipment is used for charging. Extremely large potentials with very good long term stability have been achieved. This paper presents results of charging SiO₂ and CYTOP electret films by a so-called ionic hairdryer. Maximum charge density of 34 mC/m² for SiO₂ and 2 mC/m² for CYTOP has been shown.

Keywords: Electrostatic vibration energy harvester, electrets charging, charge stability

three times to get up to 11.5 µm CYTOP film thickness (multi-layers of CYTOP).

1 INTRODUCTION

Charging of electrets is an essential step for MEMS based capacitive vibration energy harvester [1]. CYTOP [2] and SiO₂ [3] are widely used electret materials in miniaturized energy harvesters. SiO₂ electrets have good charge storage stability and can work in harsh environment. Electrets are typically charged by corona charging [2], but also ion implantation was successfully used for charging SiO₂-electrets [4].

Demands on electrets and charging of electrets are high charge capacity (i.e. charging up to potential corresponding to the breakdown dielectric strength of the electrets), short charging time, no degradation of electret by charging, long term stability, robustness against environmental conditions and low cost (apparatus and material cost). For future large scale use of MEMS based capacitive vibration energy harvester also the capability of recharging at the customer side might be an important criteria for choosing electrets and charging of that electrets.

In this paper we will present charging results for SiO₂ and CYTOP electrets with commercial so-called ionic hairdryers which provide a large amount of ions at very low costs.

2 EXPERIMENTAL SET-UP

2.1 Fabrication of Samples

For all samples 10 - 15 Ωcm boron doped (100) silicon wafers (4") were used. Samples were either oxidized using wet oxidation at 1000° C (thicknesses 0.5 µm and 1.5 µm) or spin coated with 3.5 µm - 11.5 µm CYTOP. For CYTOP deposition the following procedure was chosen: After cleaning and spinning on of TI-Prime adhesion promoter (4250 RPM; 25 s; followed by 115°C hot plate for 2 min), 3.5 µm CYTOP was deposited by spin coater (CYTOP CTX-8009A; 1000 RPM; 40 s), followed by a hard bake in an oven. To avoid bubbles in the CYTOP during hard bake, the temperature was increased in steps (after starting the hard bake with 50°C for 30 min, every 10 minutes the temperature was increased to 70°C, 90°C, 110°C, 130°C, 150°C and 180°C. The final bake at 180°C was done for 1.5 hours). This process is repeated up to

2.2 Charging of the samples

The charging was done using OEM components used in hairdryers or with commercial hair dryers without special changes. Additionally, a so-called air ionizer was tested. Here we will present results using commercial hairdryers.

In hairdryers charges are produced from thermionic-based emission (standard) and/or applying high voltage (some kV) at special tips within the air flow (ionizing option). Whereas for thermionic-like emission only moderate amounts of charges (positive and negative) can be produced, modern ionic hair dryers can generate single polarity of ions very effectively. Generation up to 65 million ions/cm³ using high voltage components has been reported [5]). In these devices a needle-like electrode connected to 4 – 8 [kV] DC is used which is arranged near the hairdryer air outlet, to reduce the distance between ionizing device and the hairs. The inbuilt fan of the hairdryer ensures transportation of the ions to the wafer [6, 7].

For this research, charging was done with a commercial ionic hairdryer (Braun Satin Hair 3549) in a plexiglass housing with ventilation holes to allow exit of the air flow from the hair dryer. Two different charging set-ups were proved to charge up the wafer surface with a negative potential only and are shown in Fig. 1a and Fig. 1b: Either direct charging with a hair dryer just connecting the wafer to ground (Fig. 1a) or charging through an extra grid (at negative potential in respect to wafer) placed between hair dryer outlet and Si-wafer (Fig. 1b). Additionally, OEM components (needles with -7.5 kV voltages, AIR Purifier, Edion SW750) were used to realize a set-up similar to Corona charging for large areas (full wafer size) but at very low costs.

The surface potential measurements were done with an electrostatic voltmeter (Model 541-1, TREK, USA) at the recommended distance of measurement tip to wafer of 3 mm. Thus, a measurement will integrate over an area of some mm (aerial resolution of the measurement). Additionally, a temperature sensor was placed

near the wafer surface to measure the temperature during charging. For comparison, the temperature was also measured directly on the wafer using an IR-temperature sensor from TESTO.

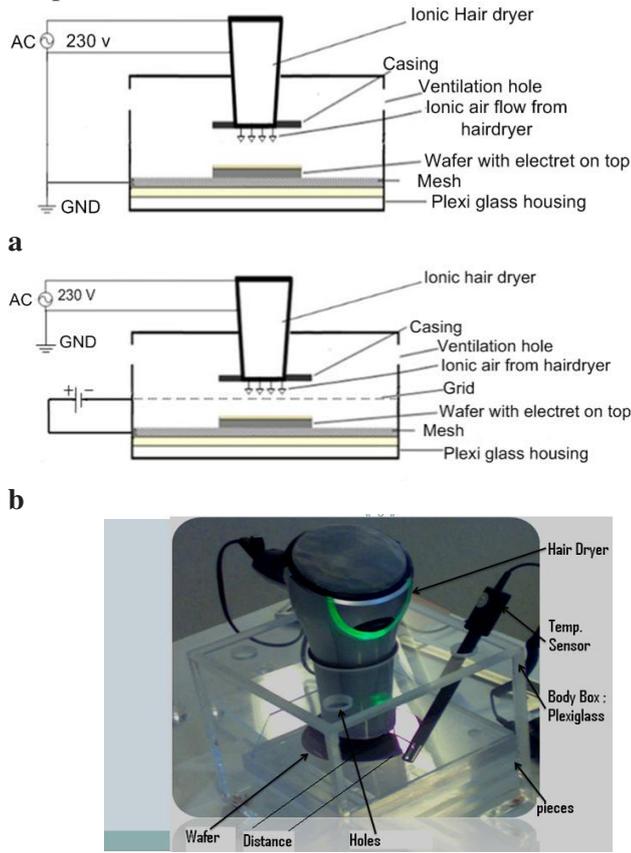


Fig. 1: Charging with hair dryer: wafer grounded (1a), extra grid between dryer outlet and wafer surface (1b); a photo of the set-up is shown in (1c).

3 EXPERIMENTAL RESULTS

3.1 Charge homogeneity and charging time

Whereas charging without ionizer function of the hair dryer results in rather low charging of the surface (positive and negative, some 10 V), with ionizer function single polarity of about -1000V were achieved, both for CYTOP and SiO₂. In the case of 0.5 μm thick SiO₂, this is considerable larger than for corona charging and ion implantation.

From the achieved surface potential U and for the given electret thickness d_{el} the charge density σ can be calculated:

$$\sigma = \epsilon_0 \cdot \epsilon_{el} \cdot U / d_{el} \quad (1)$$

A maximal charge density of 34 mC/m² is derived for SiO₂ which is more than double of the value achieved by ion implantation where a clear saturation of the charged potential and charge density was observed when increasing the total implantation dose [4]. The maximal charge density for CYTOP using this new charging principle is about 2 mC/m², almost three times more than reported for Corona charging [2]. However, only with proper grounding or grid voltage applied (compare Fig. 1), reliable results are found. Due to the simple set-up, the homogeneity of potential

or charge density over a full 4" wafer is rather poor, with a spread of typically 30-50% around mean value. A typical example is shown in Fig. 2a (maximal potential: -629 V, mean:-442 V, standard deviation σ_{st}=141V). Homogeneity is similar for the investigated set-ups (grounded wafer and grid arrangement, Fig. 1a and b). The homogeneity can be increased by rotation of wafer during charging (Fig. 2b, maximal potential: -754 V, mean: -584 V, σ_{st}=96 V).

Charging rate and homogeneity depend on the distance between hair dryer output and wafer surface. Typically, distances of 12-35 mm were chosen. For the used conditions a typical charging time of about 30 min is sufficient to reach maximal potential at these conditions (Fig. 3). The plotted values correspond to the maximal value found on each wafer (compare Fig. 2a). For 1.5 μm thick thermal oxide, saturation is not finally reached. Therefore, the corresponding charge density σ calculated with eq. (1) is 20 mC/m² (U= -867 V), which is still below the value for 0.5 μm SiO₂ (34 mC/m², U= 500 V).

The maximal charged voltage depends on the thickness of the used electrets as expected for a breakthrough-limited maximal surface potential. E.g. the maximal potential can be increased from -500 V to -796 V by increasing the SiO₂-thickness from 0.46 μm to 1.49 μm (charging with grounded wafer, distance 25 mm, charging time 30 min). For CYTOP, the corresponding values follow the relation of thickness (d= 3.6 μm, average potential: -442 V; d = 7.8 μm, average potential: -778 V, distance: 12 mm, grounded wafer).

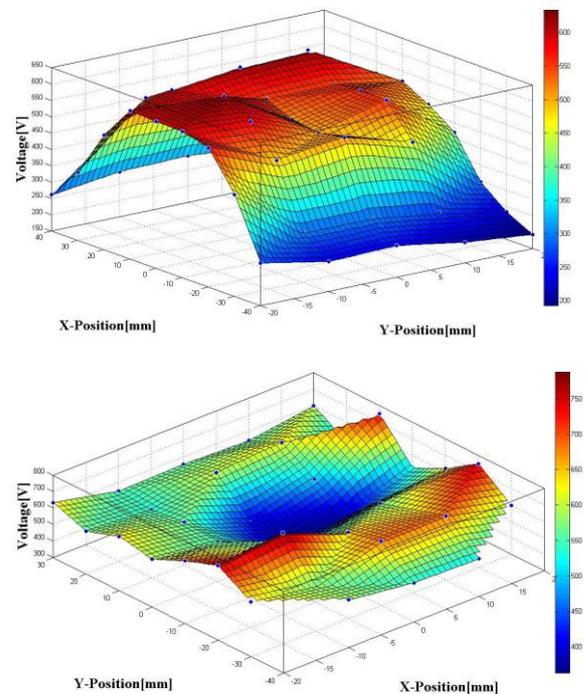


Fig.2: Homogeneity of surface potential directly after charging. Top: CYTOP, bottom: SiO₂ with wafer rotation between 4 charging cycle (each 8 min), distance 12 mm, wafer grounded.

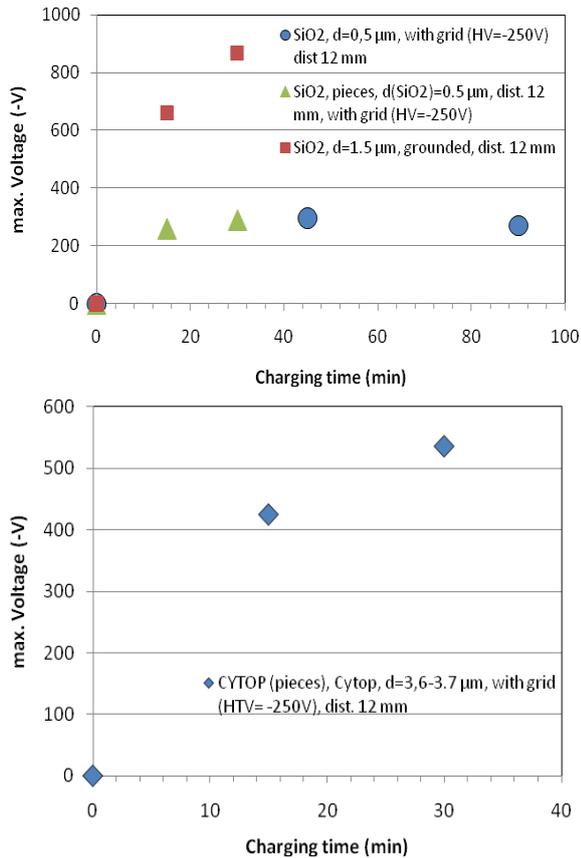


Fig. 3: Maximal achieved potential as function of charging time (saturation like behavior, top: SiO₂, bottom: CYTOP, charging with grid potential of -250V at distance of 12 mm)

3.2 Long term and temperature stability

Long term stability of the provided charge is essential for using a charging technique for energy harvesters. The relative voltage drop for SiO₂ charged with an ionizing hair dryer is considerable less than for charging SiO₂ by ion implantation. Where for the latter case about 25% (range of 10-50%, depending on initial potential) of the charge is lost within 50 days (and for a typical starting potential of 150 V only) [4], charging by ionic hair dryers create long term stable charges: the relative loss after 50 days is less than 20% even for very large starting potentials of more than 800V. The loss depends only slightly on the starting voltage as shown in Fig. 4a. For CYTOP, the de-charging behavior is more pronounced, especially for larger starting voltage of more than -1000V (Fig. 4b). In Fig. 4, the maximal potentials on the corresponding wafers are shown which is a kind of worse case scenario in respect to long term losses of charges. This has been proven for SiO₂ by measuring a complete wafer surface and then averaging over all locations: Starting with an average potential of -526 V with a standard deviation of 132 V (d(SiO₂)=1.48 μm, charged at a distance of 12 mm for 15 min) the average value decreases to -459 V (87% of starting potential) and the standard deviation to 94 V after 139 days. The decrease of averaged value is therefore smaller than the decrease of the maximal values shown in Fig.4.

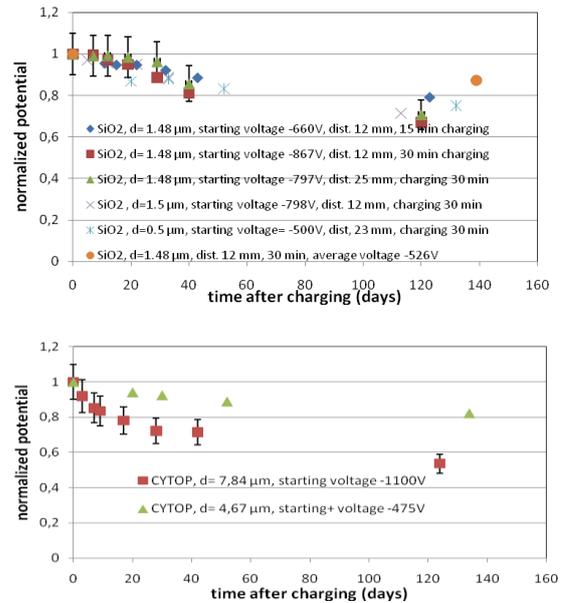


Fig 4: Long term stability of ions charge by ionic hair dryers; a) for SiO₂, b) for CYTOP. The potential is normalized to the starting potential (max. value) directly after charging. Error bars indicating typical errors due to local potential variation (Fig. 2a).

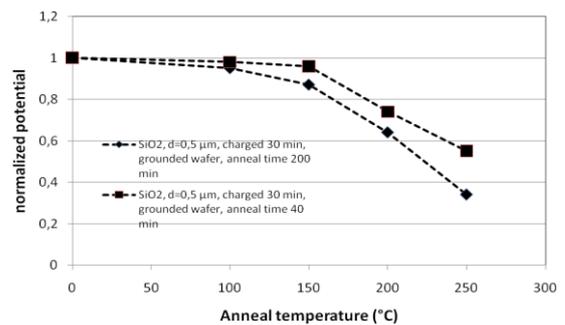


Fig. 5: Temperature stability of charge on SiO₂. The charges samples were annealed in an oven for 200 min. at the given temperatures.

Comparing CYTOP (thickness of 7.84 μm and 4.67 μm, corresponding maximal potentials of about -1100 V and -475 V, respectively) and SiO₂ (thickness 0.5 and 1.5 μm, corresponding maximal potentials -500 V and -867 V) the measurement results give strong indication that on long term SiO₂ provides larger potentials and charge densities than CYTOP for this kind of charging even though the starting potential is larger for CYTOP due to the larger film thickness.

Temperature stability has been characterized by putting charged wafers into an oven and annealing the wafers up to 200 min and measure the wafers again at room temperature. The results for SiO₂ are shown in Fig. 5. Up to 150°C, degradation of charge even for 200 min is rather low. Above 200°C, decharging of SiO₂-electrets occurs within some 10 min. These values correspond to charging SiO₂ by ion implantation [4] and show the benefit of SiO₂ as electret for commercial applications where temperature of more than 120°C should be considered.

4 DISCUSSION

The presented results show that charging of electrets with an ionic hair dryer gives better results in respect to maximal charge density and long term stability than using sophisticated (and expensive) charging principles as ion implantation or corona charging. To understand this, properties of the ions and air flow in an ionic hair dryer are considered in this section. The temperature of the air in the hair dryer's flow is between 40 and 70°C which is even for CYTOP comparable low and will not influence charge stability. The air flow velocity of the used hair dryers was measured with a thermal anemometer (TESTO 425): The free flow speed is about 7 m/s, whereas driving a hair dryer in a distance of 12 mm above the wafer, close to the wafer turbulences occur with flow speed at the rim of the wafer of 10 m/s and in the center of the wafer 2 m/s. However, this flow velocity generated by the fan of the hair dryer is considerable smaller than the average, but stochastic velocity of molecules in air at around 300K: The Maxwell-distribution gives a maximal probability of around 450 m/s [8] which is therefore at least 45 times larger than the forced and directed flow by the fan. Additionally, the average free path of N₂-molecules at atmospheric pressure is only 68 nm. Therefore, even at high potentials of 1000V achieved by charging the electrets with an ionic hair dryer, the electrostatic energy which a molecule can take up between two collision is negligible small ($5.7 \cdot 10^{-3}$ eV considering a ion at the output of the hair dryer in a distance of 12 mm from the wafer surface seeing a potential of 1000 V) and far less than the kinetic energy of the molecules due to their stochastic movement ($3 \cdot 10^{-2}$ eV). Furthermore, the ion concentration ($6.5 \cdot 10^7$ cm⁻³) is rather small compared to the concentration of non-charged molecules in air (around $2.7 \cdot 10^{19}$ cm⁻³), so the ions most probably will collide with neutral molecules. As a result we conclude that the kinetic energy of the ions is too low to ionize the surrounding air near the wafer and also too low to introduce any defects in the surface of the SiO₂. Whereas the first aspect is important to get a single polarity charging (i.e. negative), the last aspect might explain the excellent long term stability of SiO₂ charged with ionic hairdryers compared to charging by ion-implantation or corona charging even at potentials which create electric fields above the electrical breakthrough of 500 kV/mm reported in literature [9]. Additionally, due to the differences in the corresponding energies (stochastic: $3 \cdot 10^{-2}$ eV, electrostatic energy between two collisions: $5.7 \cdot 10^{-3}$ eV) the built-up surface charge will have only slight influence on the movement of the ions which explains that it is possible to charge up the surface up to 1000 V at atmospheric pressure.

Therefore, the only disadvantages of the proposed new charging technique are the inhomogeneity over large wafer surfaces and the restricted possibility to control the maximal potential exactly. However, the

first disadvantage can be avoided by relative movement of wafer and hair dryer. A control of the final charged potential can be achieved by using charging times well above saturation time. As this saturation occurs typically at around 30 min, the according charging times are still reasonable.

5 CONCLUSION

The presented new technique of using ionic hairdryers for charging electrets in capacitive vibration energy harvester provides excellent charging results. Maximal charge density for SiO₂ (34 mC/m²) is found to be about two times larger than for ion implantation and even around three times larger than corona charging for CYTOP (2 mC/m²). Due to low energy charging, charges are very stable, especially in SiO₂. So this simple technique available in every household provides specific charging properties which are better than sophisticated charging methods such as ion-implantation or corona charging.

The new technique is used for a new type of MEMS based capacitive vibration energy harvester set-up where the electret (SiO₂) is formed on vertical side-walls of a comb like movable electrode.

As a future application, this technique can be used for recharging the electrets in MEMS harvester by the customer.

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