

# Electric surface potential and frozen-in field measurements in thermally poled silica

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**Abstract:** Surface potential (SP) as well as nonlinear optical coefficients in thermally poled silica were measured and compared. It was found that the SP is directly related to the frozen-in voltage across the depletion layer.

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## 1. Introduction

Thermal poling of silica-glass is an efficient technique for inducing a second order optical nonlinearity (SON) [1], in an otherwise centro-symmetric material and is of great interest for wavelength conversion and electro-optic modulation in silica fibers. Several works [2-4] have concentrated on the actual process lying behind thermal poling, showing how two charged layers form inside the sample and give rise to a frozen-in voltage ( $V$ ). Efforts have also been made to establish the values of  $V$  and of the internal electric field ( $E_{in}$ ). This latter is directly proportional to  $V$  through the relation:  $V = E_{in} L$ , where  $L$  is the depletion layer or space charge region thickness where most of  $E_{in}$  is concentrated. The value and optimization of  $E_{in}$  in the depletion layer are crucial to infer and thus optimize the SON. In fact it is now widely accepted that the nonlinear optical coefficient ( $d_{eff}$ ) is directly proportional to  $E_{in}$  via the third order nonlinear susceptibility ( $\chi^{(3)}$ ) according to the relation:  $d_{eff} = 3/2 \chi^{(3)} E_{in}$ .

In this work we investigate, for the first time to our knowledge, the temporal evolution of the surface potential (SP) and its dependence on sample thickness in thermally poled glass. Through SP measurements on both anodic and cathodic sides, we calculate the space charge distribution and find out that additional screening surface charge layers are needed to explain the results. The value of  $E_{in}$  and its evolution with poling time is thus calculated and compared with those measured through second harmonic generation (SHG). Despite being large,  $E_{in}$  is still about three times smaller than that required to justify  $d_{eff}$  measured through SH, according to the above relation. This is probably due to a non perfect 'evaporation' of screening charges during re-heating, thus effectively reducing the measured SP and the inferred  $E_{in}$ , this effect being larger for thinner samples.

## 2. Experiments

Samples of fused silica of different thickness (0.1, 0.5 and 1 mm) were thermally poled over a 1 cm<sup>2</sup> area in air at 270°C, 4 kV and for various poling times: 2, 5, 10, 20, 30, 45 and 90 minutes. SP measurements were carried out using an earthed field-meter (JCI 140CF, John Chubb instrumentation) calibrated against a metal plate of same dimensions (1 cm<sup>2</sup> area) to which a known potential was applied (fig.1). SH measurements were carried out through the Maker's fringes technique which allowed an evaluation of the nonlinear thickness (that we identify with the depletion layer thickness,  $L$ ) and  $d_{eff}$  [5].

We observed a high SP (~1 kV) in the first minutes after thermal poling and cooling the sample. The SP then slowly decreased to negligible values in about 10 minutes. We believe that this is due to the formation of screening charge layers of atmospheric particles (mainly surface H<sub>2</sub>O, i.e. H<sub>3</sub>O<sup>+</sup> and OH<sup>-</sup>, and electrons, depositing on both sample sides). This is also supported by the fact that, while SP died off during

cooling, the SHG signal remained constant, thus indicating that  $V$  was not changing. This surface charge neutralization is a well known mechanism, for example in ferroelectrics, such as  $\text{LiNbO}_3$  and  $\text{LiTaO}_3$ .

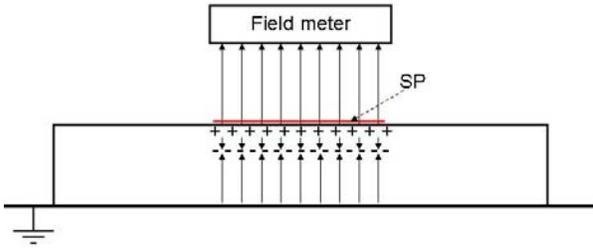


Fig.1 Set-up and geometry of SP measurements from anodic side using a field meter.

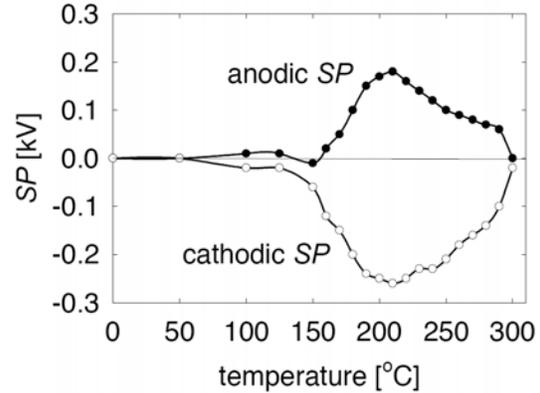


Fig.2 Measured anodic and cathodic surface potentials for a silica slide thermally poled at 270°C, 4 kV and 10 minutes.

In order to be able to re-measure SP, we tried heating up the samples. We increased the temperature in 10°C steps and repeated the SP measurement for both the anodic and cathodic faces at each step. All samples showed the same behavior: an example is reported in figure 2. Below 160°C the SP remains zero but above this temperature it begins to increase due to a likely “evaporation” of the screening surface charge layers. A maximum value was reached for 210°C, then SP started to decrease once again, suddenly returning to zero as the poling temperature (270°C) was reached. Furthermore, the SH, measured at each step, remained constant and only started to decrease above 210°C thus indicating that we started erasing  $E_{in}$ , i.e. the internal voltage  $V$ . Note that, as expected, positive values of SP are measured from the anodic face and negative values from the cathodic face.

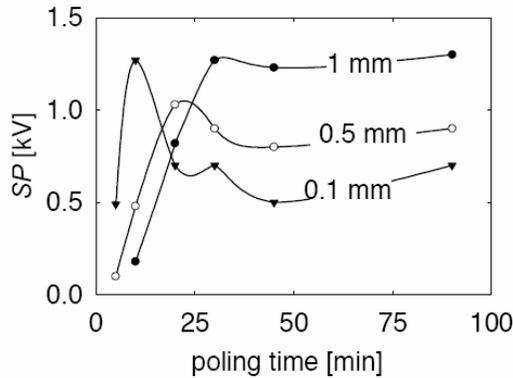


Fig. 3 Anodic SP evolution with poling time for samples of different thickness. The lines are only a guide for the eye.

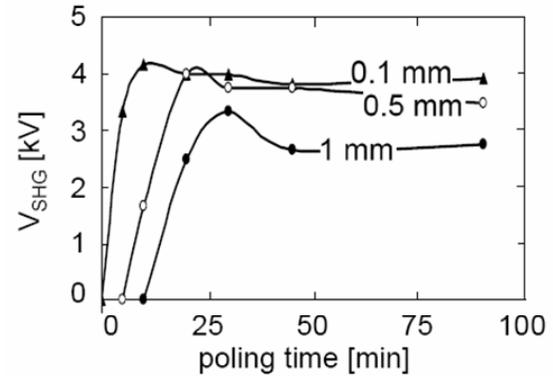


Fig. 4 Calculated  $V$  from SHG and its evolution with poling time for samples of different thickness. The lines are only a guide for the eye.

The SP values are functions of sample thickness and poling time (fig.3). In fact values of 1.3 kV for SP have been measured, meaning that a significant fraction of the voltage (4 kV) applied during poling is actually stored inside the sample. We believe this is the first time that such direct quantitative measurement of  $E_{in}$  is provided in silica. The difference between SP and applied voltage is probably due to a non perfect ‘evaporation’ of screening charges during re-heating as well as to fringe field effects, thus effectively reducing the measured SP. This was partly confirmed by measurements performed on samples with a much larger poled area. In this case, the obtained SP values are closer to the applied voltage, as the fringe field effects are then reduced.

Fig. 4 shows the evolution for the frozen-in voltage  $V$ , as a function of poling time and thickness, measured through SHG Maker’s fringes technique (which we name  $V_{SHG}$ ). Contrary to an intuitive picture, if one compares SP and  $V_{SHG}$  evolutions (figs. 3 and 4) some clear differences exist, in particular a reverse trend with respect to sample thickness for poling times larger than 30 min. However one should bear in

mind that SP is measured with samples at a certain temperature while  $V_{\text{SHG}}$  comes from room temperature SHG measurements. The two situations might thus present a different surface charge screening which depends on temperature and poling thickness.

### 3. Modeling and interpretation of experimental results

To investigate these differences we have calculated the charge distribution from SP measurements using FEM analysis. Initially we have assumed two charge layers, one negative ( $\sigma^-$ ) below the anodic surface (at a depth  $L$  calculated using SH measurements) and one positive ( $\sigma^+$ ) on the anodic surface. From high temperature (hot) SP values on both anodic and cathodic sides, we have calculated the evolution of both  $\sigma_{\text{hot}}^-$  and  $\sigma_{\text{hot}}^+$  with poling time and sample thickness.  $\sigma_{\text{hot}}^-$  and  $\sigma_{\text{hot}}^+$  are similar and oscillate between  $10^{-9}$  and  $10^{-8}$  C/m<sup>2</sup> (depending on poling time and sample thickness).

To be consistent with room temperature (cold) SP measurements, we have then recalculated  $\sigma^+$  ( $\sigma_{\text{cold}}^+$ ) by keeping the same value for  $\sigma^-$  ( $\sigma_{\text{cold}}^- = \sigma_{\text{hot}}^-$ ). The values of  $\sigma_{\text{cold}}^+$  are smaller than  $\sigma_{\text{hot}}^+$ , this difference being greater for smaller sample thicknesses. For 1 mm thick samples,  $(\sigma_{\text{hot}}^+) - (\sigma_{\text{cold}}^+)$  is 2 to  $4 \times 10^{-11}$  C/m<sup>2</sup> while for 0.1 mm samples the difference is increased of about 10 times. In order to have negligible SP on both faces at room temperature, one also has to introduce a very small positive surface charge (value close to  $(\sigma_{\text{hot}}^+) - (\sigma_{\text{cold}}^+)$ ) on the anodic side (back side). Note that more charges have to ‘evaporate’ to reveal SP for thinner samples. This might be the reason why SP for thin samples (fig. 3) measured in the hot situation are usually smaller than those for thick samples, although the frozen-in voltage measured from SHG in cold situation has an opposite trend (fig.4).

From the room temperature (cold) charge distribution, we have calculated the internal field ( $E_{\text{in}}$ ) in the depletion region ( $\leq 0.35$  kV/ $\mu\text{m}$ ) and consequently  $d_{\text{eff}}$  ( $\leq 0.1$  pm/V). These values are about 3 times smaller than the corresponding ones measured through SHG.

### 4. Conclusions

We have reported, for the first time to our knowledge, measurements of surface potential in thermally poled silica samples. The inferred internal electric field ( $E_{\text{in}} \leq 0.35$  kV/ $\mu\text{m}$ ) in the depletion region and the corresponding nonlinear coefficient ( $d_{\text{eff}} \leq 0.1$  pm/V) follow the behavior predicted by SHG measurements, provided that screening surface charges are taken into account. The difference in values of  $E_{\text{in}}$  and  $d_{\text{eff}}$  between SP and SHG measurements (values from SP about 3 times smaller than those from SHG) is likely to be due to an underestimate of SP as a consequence of non perfect evaporation of screening charges. This is also in agreement with the opposite trend of SP and  $V_{\text{SHG}}$  with respect to sample thickness if one bears in mind that the thinner the sample the higher the quantity of charge that needs to “evaporate” to reveal the frozen-in voltage in terms of SP.

### 5. References

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