Some Properties of Field Ion Emission from SiO$_2$ Grains

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Abstract. Probably the most abundant dust in space constitutes silicates. When the dust grain is exposed to energetic electron or ion beams it can attain a large surface potential which is limited by field ion emission. It is generally expected that the field ion emission is controlled by the surface electric field, and pressure and composition of the ambient atmosphere.

In our study, we have used spherical glass dust grains with diameters around 1 micron charged to several kV. Such charging creates the electric field in the range of $10^9$ V/m leading to observable field ion emission. A positive charge of the dust grain can be reached not only by ion bombardment but, under some circumstances, by electrons as well. Contrary to the expectations, when charged by electrons, the discharging characteristics depends on the obtained specific charge, the energy of impinging electrons and charging current density. Moreover the discharging shows an increase of the discharging current in the beginning. We show that such behavior is caused by diffusion of positive holes inside the grain through the influence of an inner electric field and enhanced temperature.

Introduction

Field ion emission is discharging process inherently connected with high-intensity electric field usually occurring at highly curved surfaces such as sharp tips or edges and small dust grains. It limits the maximal obtainable surface potential. There are three main processes playing a role in field ion emission from positively charged objects. They are field ionization (ionization of atoms from surrounding atmosphere), field desorption (ionization of atoms desorbed from the surface) and field evaporation (ionization of atoms evaporated from the bulk due to the electric field). It is usually considered that emission currents are controlled by the electric field only [Gomer, 1961], but other effects can take place (such as additional sources of atoms, e.g., from implanted ions [Jeřáb et al., 2010, Beránek et al., 2010]).

Previous studies [Jeřáb et al., 2010, Beránek et al., 2010, Beránek et al., 2011] of field ion emission from dust grains were made on conducting materials (gold, carbon). Aim of this work is to study discharging processes of a non-conducting dust grain, particularly small glass (SiO$_2$) spheres as the simplest shape and composition substitute of silicates that constitute a significant part of space dust.

Experimental techniques

Our experimental set-up is broadly described in previous works [Čermák et al., 1995, Žilavý et al., 1998, Pavlů et al., 2004, Němeček et al., 2011]. It consists of an electrodynamic quadrupole (Paul’s trap) capable to store a single dust grain for a long time in the UHV apparatus. Charge-to-mass ratio ($q/m$) of the levitated grain is proportional to the frequency of grain oscillations in the trap. The grain is illuminated by a red laser diode and the scattered light is focused to the position sensitive detector by a lens system. The frequency of grain oscillations is determined from this signal. Electron and ion sources are used for grain charging or discharging. The energy of the electrons and/or ions can be adjusted in the ranges of 0.1–12.6 keV.

The dust grain is charged up to several kV using electron beam and let discharge for several hours. Discharging currents as a function of the surface electric field can be calculated from a temporal evolution of the charge-to-mass ratio using numerical derivation and knowledge of capacity and mass of the dust grain. The discharging currents are normalized to the grain surface due to better comparison between various grains.
Results

Typical discharging curves are depicted in Figure 1. Sharp decrease of discharging currents is observed below $2.5 \times 10^9$ V/m with a step around $1.3-1.75 \times 10^9$ V/m. As it can be seen in Figure 1, the maximum discharging current does not depend on attained specific charge above $4 \times 10^9$ V/m. It implies that all charge carriers leave the grain and there is no other charge carriers that could contribute to the discharging current. A possible explanation is that the limit is given by the ambient pressure (there are no other atoms that can be ionized). It could be interesting to reach even higher potential at which the field evaporation would occur.

Discharging currents at a given electric field intensity (e.g., $2 \times 10^9$ V/m) depend on the energy of impinging electrons (Figure 2), charging current density (Figure 3), and attained specific charge (Figure 4 left). Generally, a higher specific charge leads to lower discharging currents and the higher energy of impinging electrons leads to lower discharging currents as well (it is important to note that the difference is smaller when the discharging starts from the higher specific charge). When the charging current intensity is higher, the discharging current is higher, too.

The discharging current generally decreases with time but an unexpected increase of the discharging current at the beginning of discharging was observed repeatedly for electron charging of non-conducting glass grains. Figure 4 shows several discharging characteristics (points) of the non-conducting glass grain charged by energetic electrons (11.9 keV) as a function of the surface field (left) and time (right). In Figure 4, it is possible to see that an increase of the discharging current depends on the electric field intensity. We have fitted measured data by an exponential increase of the discharging current in time according to Equation 1. Discharging current $j$ at time $t$ depends on maximal discharging current $j_{max}$ and time constant $b$.

$$j = j_{max} \left(1 - \exp \left(\frac{t}{b}\right)\right)$$ (1)

Fits are plotted as lines in Figure 4. The time constants $b$ obtained from the fits are listed in Figure 4 (right). It is obvious that the time constant depends on obtained surface electric field.
**Figure 2.** Field emission from glass dust grain when charged by various energies of electrons (constant charging currents). Left—diameter 1.02 µm, constant specific charge 55 C/kg, $E = 12.00$ keV (light gray), $E = 12.20$ keV (gray) and $E = 12.50$ keV (black). Right—diameter 1.00 µm, constant specific charge 70 C/kg, $E = 11.81$ keV (light gray), $E = 12.20$ keV (gray), $E = 12.40$ keV (dark gray), $E = 12.60$ keV (black).

**Figure 3.** Field emission from glass dust grain with diameter 1.00 µm when charged by various electron currents (constant energy of 12 keV and specific charge of 69 C/kg). The currents are $i_8 \times 1$ (full circles), $i_9 \times 1$ (empty circles), $i_{10} \times 1$ (full triangles) and $i_{11} \times 1$ (empty triangles). Note that there are 3 current levels per decade, i.e. $i_8 \times 1$ and $i_{11} \times 1$ differ by an order of magnitude. Current densities are in the order of 10 nA/mm$^2$.

**Explanation**

Secondary electrons are emitted from a whole volume of a grain (about 70 % of the electrons flight through the grain at 12 keV [Richterová et al., 2010]). The missing electrons create positive holes (as it is schematically depicted in Figure 5) serving as charge carriers. Their diffusion toward the surface is slow in a non-conducting material. But the impinging electrons lost a part of their energy in the grain. This energy cannot be radiated from the grain due to very low glass emissivity in the infrared region and the grain can reach many hundreds of K leading to higher mobility of the holes. Moreover, the positive holes create the electric field inside the grain leading to an ambipolar diffusion.
Figure 4. Discharging characteristics of glass grain (diameter 1.02 \( \mu \text{m} \)) charged by energetic electrons (11.9 keV) to different charge-to-mass ratios as a function of the surface field (left) and time (right). The charge-to-mass ratios are: 60 C/kg (light gray), 70 C/kg (gray), 80 C/kg (dark gray), 90 C/kg (black). Time constants (in seconds) obtained from Equation 1 are listed at respective line.

Figure 5. A schematic description of the model. Impinging electrons flight through the grain leading to the secondary emission (left). After stopping of the electron beam, there are many positive holes inside the grain (middle). The enhanced temperature and high inner electric field lead to diffusion of the holes toward the surface (right).

Holes in the near surface region constitute sites for capturing electrons from atoms of the surrounding atmosphere. An increasing number of holes near the surface increases the ionization probability leading to higher discharging currents. Hence discharging currents are controlled by holes influx that is affected by changes of inner electric field and temperature. The hole control mechanism take effect up to maximum discharging current that is given by ambient pressure making limit of outgoing charge.

Discussion

When the electron beam is on, a part of secondary electrons returns to the surface due to its positive charge. These electrons recombine with the positive holes leading to lower hole density in the near surface region. After switching off the electron beam the number of holes increases due to theirs diffusion causing increase in discharging current. In a certain time (given by the time constant \( b \) in Equation 1) the hole income and recombining by ionization of the surrounding atmosphere reaches equilibrium and the discharging current reaches maximal value.

As has been mentioned above, impinging electrons heat up the grain through dissipating of theirs energy and consequently the enhanced temperature speeds up the diffusion of holes. Such effect is observed in Figures 2 and 3. Higher impinging electron energy leads to faster charging. The grain reaches lower temperature and the diffusion is slower. Consequently the holes are frozen deeper under the surface hence causing lower discharging current (Figure 2). Higher charging currents lead to a higher grain temperature that speeds up the diffusion (Figure 3).

Figure 4 shows that if the grain discharging starts from a higher charge-to-mass ratio, the discharging current corresponding to a particular electric field intensity is lower. Time from the
beginning of discharging to the reaching of particular field intensity is longer for grain charged to higher charge-to-mass ratio. The grain gets colder and hole influx to the surface is lower. It leads to lowering of the discharging current despite faster initial diffusion of the holes due to the higher electric field intensity inside the grain at the beginning. Faster diffusion of holes at a stronger electric field is indicated by smaller values of time constants (Figure 4 right).

Conclusion

Field ion emission currents start with the current increase after the electron bombardment of glass dust grains and a saturated discharging current (probably given by the ambient pressure) can be observed. Emission currents depend on attained charge-to-mass ratio (higher charge-to-mass ratio leads to lower currents), impinging electron energy (higher energy causes lower currents) and charging currents (higher charging currents leads to higher emission currents). Such dependencies are consistent with the hole formation mechanism (impinging electrons produce positive holes in the bulk of the grain; these holes diffuse toward the surface where they cause discharging). The initial increase of the emission current is caused by the diffusion of holes (as surface region is depleted in holes due to recombination with returning electrons), higher charge-to-mass ratio leads to stronger inner electric field (faster initial increase of the discharging current) and longer discharging time (lower temperature and slower diffusion, the holes can eventually froze deeper in the bulk). Higher impinging electron energy causes shorter charging time and hence lower temperature (lower hole mobility) and higher charging currents leads to higher temperature (higher hole mobility).

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References


