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Microwave breakdown of low pressure N_2 gas in microgaps

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The pressure dependence of the breakdown of nitrogen gas by a microwave field in microgaps down to 13 μm has been measured. Fits to a phenomenological function suggest that microwave breakdown in small gaps requires a higher collision frequency, ν_c. If the effective electric field on an electron in a microgap is interpreted as $E_{eff} = E_o\sqrt{\nu_c^2/(\nu_c^2+\omega^2)}$ and then as the gap size is reduced, we find that the collision frequency needed to produce a minimum breakdown electric field shifts from $\nu_c = \omega$ for large gaps to $\nu_c = 2\omega$ for small gaps. © *2011 American Institute of Physics*. [doi:10.1063/1.3641900]

Conditions for microwave (10^8 Hz $<$ f $<$ 10^{11} Hz) breakdown influence the design and operation of signal transmission devices, antennas, and filters. Microwave induced microplasma is useful for sterilizing medical devices, depositing films, and etching semiconductor devices. Breakdown in microgaps (<1 mm) is of interest as development proceeds in microplasma sources both at DC (Ref. 1) and microwave[2] with attention focused more on the small gap DC departure from Paschen's law.[3] The breakdown electric field in a gap is usually smaller at microwave than at DC due to space charge buildup.[4] High pressure microwave discharges in microgaps have been previously examined in order to model the plasma impedance.[5] In this paper, nitrogen microplasmas are examined in order to understand the microwave breakdown condition, in particular the pressure for which the threshold breakdown electric field E_{bd} is a minimum.[6]

Measurements of E_{bd} were made around 2 GHz in a foreshortened quarter-wave resonator similar to the one described earlier.[7] The cone shaped copper resonator with a 40 μm diameter flattened tip in Fig. 1 was enclosed in an aluminum housing with a critically matched antenna bringing in high incident power, P_{inc}, at resonance and a weaker antenna transmitting some of this power to a diode detector. A brass tuner disk opposed to the end of the cone is mounted to the cavity wall on a 3 turn/mm screw permitting gap size control to within about 10 μm. A window in the housing can be viewed through a vacuum system viewport, enabling spectroscopic analysis. Breakdown is detected by a sudden drop in transmitted power. By exciting the resonator and slowly raising the power level, the microwave power that induces breakdown can be measured repeatably with the resulting breakdown curves in Fig. 1 exhibiting a minimum around 3 Torr.

In order to anticipate breakdown, consider a gas containing a small number of ions and free electrons. Charged particles oscillate in an alternating field of frequency $\omega/2\pi$. Electrons move in the electric field, E_o, as if they were in an effective electric field[8]

$$E_{eff} = E_o\sqrt{\nu_c^2/(\nu_c^2+\omega^2)}, \tag{1}$$

where ν_c is the collision frequency for momentum transfer and is linearly proportional to pressure, $\nu_c = Bp$, with *frequency per Torr* proportionality constant B. At higher pressure there are more molecules per volume, N. Larger N means there is less electron kinetic energy gained between collisions and thus a higher applied field, E_o, is needed to reach breakdown. So, the E_{eff} at breakdown increases with N as $E_{eff,bd} \propto N^m$, where the power law, m, corresponds to electron energy loss per collision and is discussed throughout this paper. This power law is substantiated physically by comparing E_{eff} at breakdown for different gap sizes to pressure in Fig. 2. Because $\sqrt{P_{inc}}$ was used for E_o, Fig. 2 shows $E_{eff,bd}$ in arbitrary units. As with all measurements here and in the data of Ref. 7, a power law dependence of $E_{eff,bd}$ on pressure is found with $0 < m < 1$, validating the claim that $E_{eff,bd} \propto N^m$.

Combining Eq. (1) and $E_{eff,bd} \propto N^m$ along with the linearity between p and N gives a general, geometry independent expression for the threshold electric field

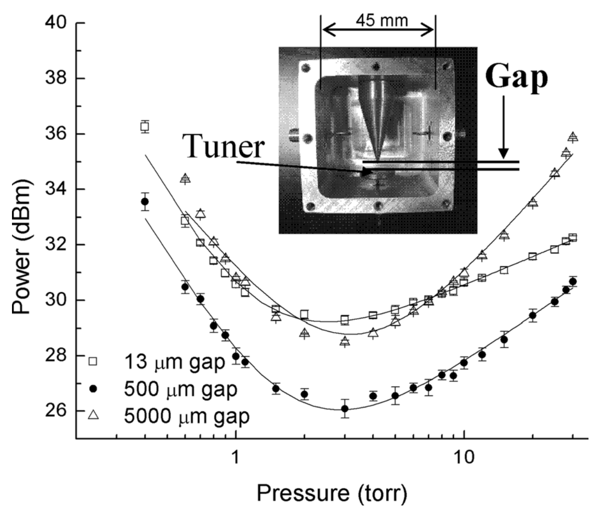

FIG. 1. Breakdown curves for gaps from three size ranges identified in this work. The curves are fits to Eq. (2). The inset shows the cone shaped resonator with antennas which can be adjusted so that one is always critically matched.

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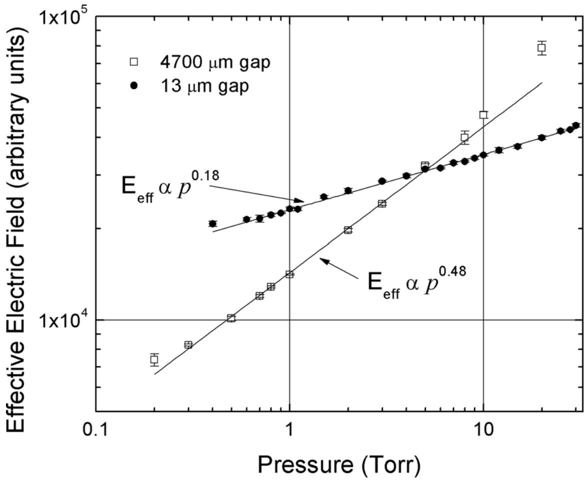

FIG. 2. Effective breakdown electric field, Eq. (1), depends in all cases as a power law on pressure and hence on molecular number density. Slope varies with gap size range.

$$E_{bd} = CP^m \sqrt{1 + \frac{\omega^2}{(B \cdot p)^2}}, \qquad (2)$$

where C is a gas dependent scaling parameter, which can depend weakly on frequency[9] but does not weigh in the conclusions of this work. The power law, m, determines the general shape of the threshold breakdown curve. Fig. 1 shows fits to Eq. (2). The fit parameter, m, is always equal to the power law found in the $E_{eff,bd}$ plots such as in Fig. 2.

Because electric field scales as $\sqrt{P_{inc}}$, it is valid to use the logarithm of Eq. (2) as the fit function in Fig. 1. Finite element analysis yielded an extremely large electric field in the smallest gaps, indicating that breakdown should occur at very small P_{inc} for small gaps. This does not correspond to the measured breakdown power, which is seen in Fig. 1, to depend only weakly on gap size. Because the scale C corresponds to the location of avalanche initiation, microwave breakdown probably does not initiate in the microgap but rather in the weaker inhomogeneous field of the open region surrounding the gap. The value of C should prove useful to pinpoint the location of breakdown in this geometry.

Breakdown at pressures above the minimum is governed by a balance between ionization and electron loss due to diffusion. Kihara's model[10] is used at higher pressures and with larger gaps.[11] Pressure dependent breakdown power above the minimum can be fit to Eqs. (48) and (49) in Ref. 12 to yield effective diffusion lengths, Λ, which range between 160 and 310 μm for gaps above 2500 μm where the field is everywhere inhomogeneous. As the gap size is reduced, Λ decreases to only 50 μm for a 228 μm gap. The breakdown curves for smaller gaps with smaller m do not fit the model of Ref. 12 at our pressures as the breakdown curves for microgaps have the wrong shape.

Fits to Eq. (2) consistently yield a power law of $m = 0.49 \pm 0.01$, provided the gap is larger than 2000 μm, as seen in Fig. 3. This was the case in Ref. 7. However, in the gap range from 2000 μm down to 250 μm, the power law gradually drops to 0.2, reflecting a broadening of the breakdown curve for microgaps. The power law exhibits an unexplained dip as the gap continues to drop down to 75 μm, but then it levels off at 0.18 ± 0.01, where it remains down to the smallest measured gap of 13 μm.

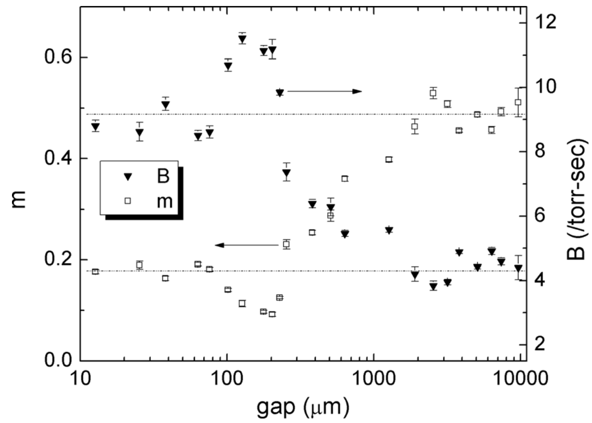

FIG. 3. Power law, m, and collision frequency per Torr at breakdown, B, were found by fitting Eq. (2). The horizontal lines are guides to the eye. Three gap size ranges were identified, with the smallest (<250 μm) being referred to in this paper as "microgap."

The collision frequency per Torr parameter, B, also shown in Fig. 3, is a gap independent 4.4 ± 0.2/Torr-s in this particular resonator, provided the gap is larger than 2000 μm. However, in the gap range from 2000 μm down to 250 μm, it rises and levels off at 8.8 ± 0.2/Torr-s, where it remains down to the smallest measured gap of 13 μm.

Differentiating Eq. (2) gives the minimum of the breakdown curves, $p_{\min} = (\omega/B)\sqrt{(1-m)/m}$, which predicts the measured minimum at other frequencies.[7] The minimum occurs at the pressure where ν_c is similar to ω.[13] Equality holds if $m = 0.5$ as is the case in large gap breakdown both for this geometry and in Ref. 7. With m shifting to 0.18 in the microgaps, the minimum occurs at the pressure for which $\nu_c \approx 2\omega$, provided ν_c in Eq. (1) can be interpreted for microgaps as the collision frequency for momentum transfer with neutral molecules. Figure 4 shows the unexpected result that the collision frequency required for breakdown, Bp, and the power law, m, are related exponentially by $m = (1.4 \pm 0.2)e^{-(0.25 \pm 0.4\ \text{Torr-s})B}$ with

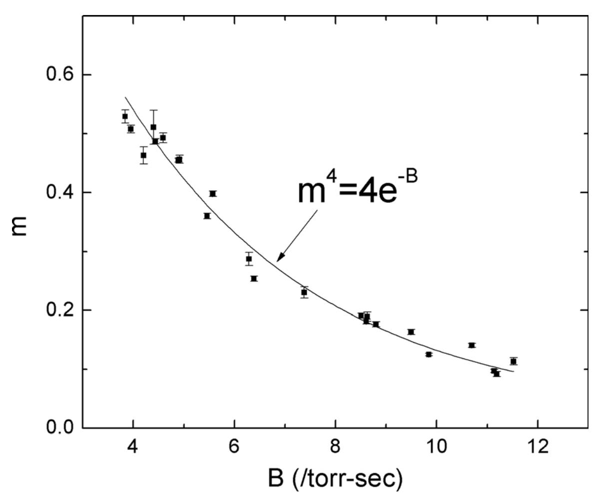

FIG. 4. The power law and collision frequency per Torr at breakdown follow an exponential relationship, $m \propto e^{-B/4}$. Gap size is implicit with the smallest gaps at the right end of the curve and the largest gaps at the left end.

gap size as an implicit parameter. Perhaps, what is referred to as "collision frequency" in the classic Eq. (1) is not exclusively electron-neutral collisions but rather any momentum transfer mechanism.

Optical spectra taken just above threshold revealed that the $B^3\Pi_g$-$A^3\Sigma_u^+$ first positive system[14] with numerous lines around 600 nm is completely suppressed in microgap breakdown but not in large gaps. Interestingly, copper peaks at 515.24 and 521.82 nm are visible and are more pronounced for small gaps, indicating some electrode sputtering. With the smallest gap size within a factor of three of the skin depth, perhaps electron collisions with the metal surfaces in microgaps inhibit avalanche breakdown inside the gap.

Below 250 μm, breakdown has been found to occur with a smaller power law, m, and a larger collision frequency, Bp, indicating a different microwave breakdown criterion for microgaps than for large gaps. Per the phenomenological Eq. (2), a change in microwave breakdown criterion appears to occur at microgaps because the rule of thumb for a minimum in the breakdown curve changes from $v_c = \omega$ for large gaps to $v_c = 2\omega$ for microgaps. Besides the noticeable difference in the breakdown criterion, a pronounced change in optical emissions of a sustained plasma occurs in microgaps with the suppression of the visible lower energy N_2 lines.

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