

Electrical breakdown limits for MEMS

The argument usually presented to show how electrical breakdown influences MEMS devices is based on Townsend (avalanche) breakdown in gases. According to this well-known theory, an electric spark can occur only if free electrons accelerated by an electric field gain enough energy between successive collisions with neutral atoms (or molecules) to ionize the atoms. Ionization releases an additional electron which also accelerates, collides with atoms, and causes more ionizations. The resulting avalanche leads to a spark. This behavior is represented by the familiar Paschen curve. The minimum in this curve occurs at the condition where the electronic mean free path is just barely sufficient to allow electrons to gain the ionization energy. Fig. 1 shows Paschen curves for air, nitrogen, and hydrogen.

For an investigation of the influence of avalanche breakdown on MEMS devices, it is reasonable to assume atmospheric conditions, that is, $p = 1 \text{ Atmos.} = 760 \text{ Torr}$: For large gaps, say one centimeter or larger gap between clean metal

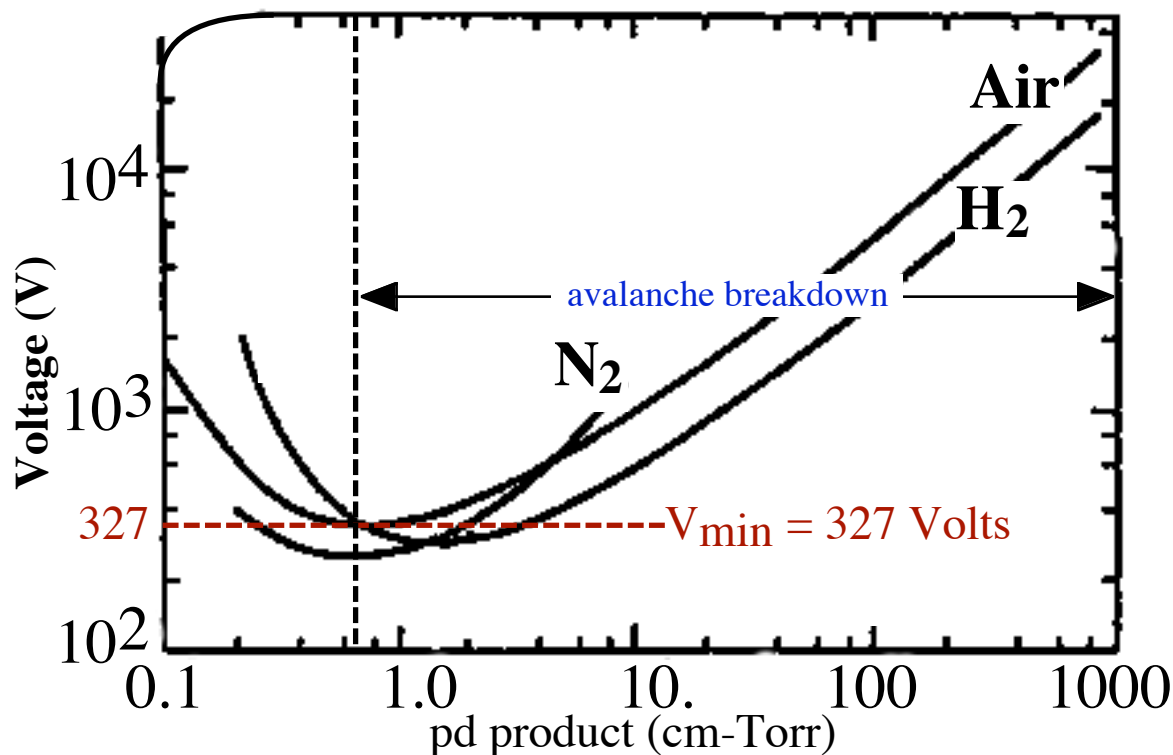


Fig. 1. The Paschen curve for dry air, nitrogen, and hydrogen. Note the significant differences between air and N_2 . (from J. D. Cobine, Gaseous Conductors, Dover, 1941).

electrodes in dry air, the generally accepted value of the breakdown field strength is $E \approx 30 \text{ kV/cm}$ ($\sim 3 \text{ V}/\mu\text{m}$). For this field strength, the volumetric electrostatic energy density is $u_e = \frac{1}{2} \epsilon_0 E^2 \approx 40 \text{ J/m}^3$, which compares quite unfavorably to the value of $\sim 4 \cdot 10^5 \text{ J/m}^3$ for magnetic devices, which is obtained by assuming a magnetic field strength of $\sim 1000 \text{ Gauss}$. But now recalculate the electrostatic energy density for conditions at the Paschen minimum in air: $V_{\min} = 327 \text{ V}$ & $pd = 0.57 \text{ cm-Torr}$ ($d = 7.5 \mu\text{m}$). The effective breakdown field strength is now:

$$E \approx 327 \text{ V}/7.5 \mu\text{m} = 4.4 \cdot 10^7 \text{ V/m}, \text{ or } 44 \text{ V}/\mu\text{m}.$$

The new value of the electrostatic energy density is $u_e = 8.4 \cdot 10^3 \text{ J/m}^3$. From this result, it is evident that reducing the size of devices to the scale of tens of microns offers the prospect that electrostatic forces can become competitive to magnetic forces.

While the above conclusion --- that electrostatic MEMS devices benefit from size reduction --- is largely correct, there are strict limits on device scaling that must be recognized. To illustrate this point, imagine a MEMS device designed to operate at STP conditions and $pd = 0.1 \text{ cm-Torr}$. If the device operates at atmospheric pressure, the gap will be $d = 1.3 \mu\text{m}$, a value for which the Paschen curve predicts a very large breakdown voltage: $V \approx 1500 \text{ V}$. The breakdown electric field value then is:

$$E \approx 1500 \text{ V}/1.3 \mu\text{m} = 1.15 \cdot 10^9 \text{ V/m}, \text{ or } 1150 \text{ V}/\mu\text{m}$$

and the electrostatic energy density rises to $u_e = 5.9 \cdot 10^6 \text{ J/m}^3$. Unfortunately for MEMS technology, this last calculation, at a gap of $1.3 \mu\text{m}$, is unduly optimistic, because it ignores field emission, another mechanism capable of creating free electrons at room temperature in the gap between two electrodes.

If the electric field at the surface of a conductor is sufficiently strong, some of the conduction electrons in the metal lattice that stray too close to the surface are literally pulled out into the gap. This effect is called field emission. The electrons, now free, respond to the normal, applied field by accelerating rapidly toward the opposite, positive electrode. Even if the mean free path is now longer than the gap, so that the electrons can not gain sufficient kinetic energy to ionize atoms of the gas, other mechanisms such as localized heating can lead to a runaway process that results in a spark. At ambient pressure and normal temperature, in gaps less than a few microns, field emission coupled with other mechanisms is known to limit useable voltages to values well below those predicted by avalanche breakdown.

The modified Paschen curve

The practical effect of field emission can be represented approximately by modifying the Paschen curve, as shown in Fig. 2. The modified curve has three

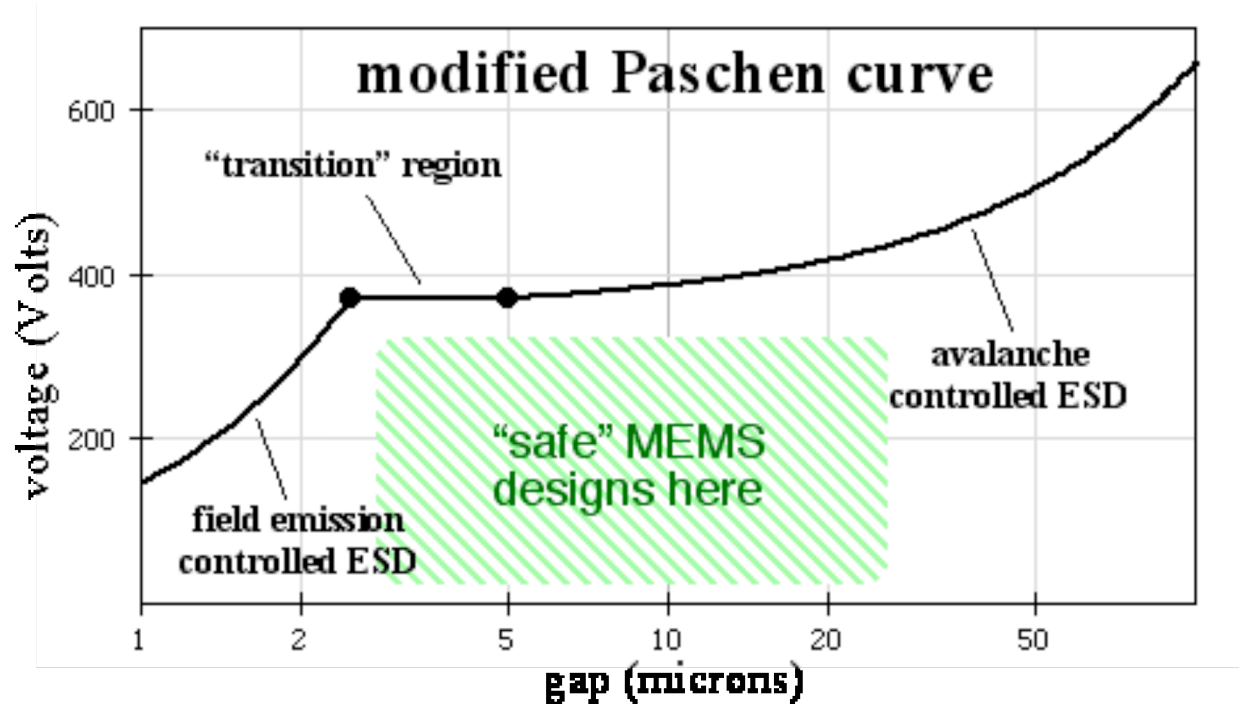


Fig. 2. Example of the modified Paschen curve proposed by Schaffert. Notice that there exists an area directly beneath the Paschen minimum where breakdown can be avoided and safe MEMS operations is possible. In this region, electric fields much stronger than the large gap breakdown field of $\sim 3 \text{ V}/\mu\text{m}$ can be sustained, meaning that the volumetric energy density is high. Note however that field emission precludes operation to the left of the minimum of the standard Paschen curve, where Townsend breakdown would predict a rise in the breakdown voltage.

regions: (i) a linear region for $d < 2 \mu\text{m}$, (ii) a flat, transitional plateau between $\sim 2 \mu\text{m}$ and $\sim 5 \mu\text{m}$ that replaces the Paschen minimum, (iii) a region virtually identical to the normal Paschen curve for $d > 5 \mu\text{m}$. There are two important observations to make about the modified curve. First, the maximum voltage is very strictly limited for values of d below the Paschen minimum. Second, there remains a region of opportunity for MEMS designs directly beneath the transitional plateau.

References

R. M. Schaffert, *Electrophotography*, (Wiley and Sons: New York) 1975, pp. 516-517.

A. Wallash and L. Levit, "Electrical breakdown and ESD phenomena for devices with nanometer-to-micron gaps," SPIE Conference, xxxx.

M. Madou, *Fundamentals of Microfabrication*, (CRC Press: Boca Raton) 1997. Chapter 9 of this text contains a discussion of scaling issues for MEMS devices.

For spacings below $\sim 5 \mu\text{m}$, the issue of breakdown become more difficult, and it is hard to find any conclusive data. At such small distances breakdown depends on field strength and, thus, the electrode geometry including such hard to characterize factors as surface roughness. At field strengths above $\sim 100 \text{ V}/\mu\text{m}$ electron field emission occurs. This mechanism can easily lead to breakdown. To my opinion, there is low risk of breakdown up to $50 \text{ V}/\mu\text{m}$ if the electrodes are free standing. However, when they are connected by an insulator, V_b is reduced.

Some good papers on the subject:

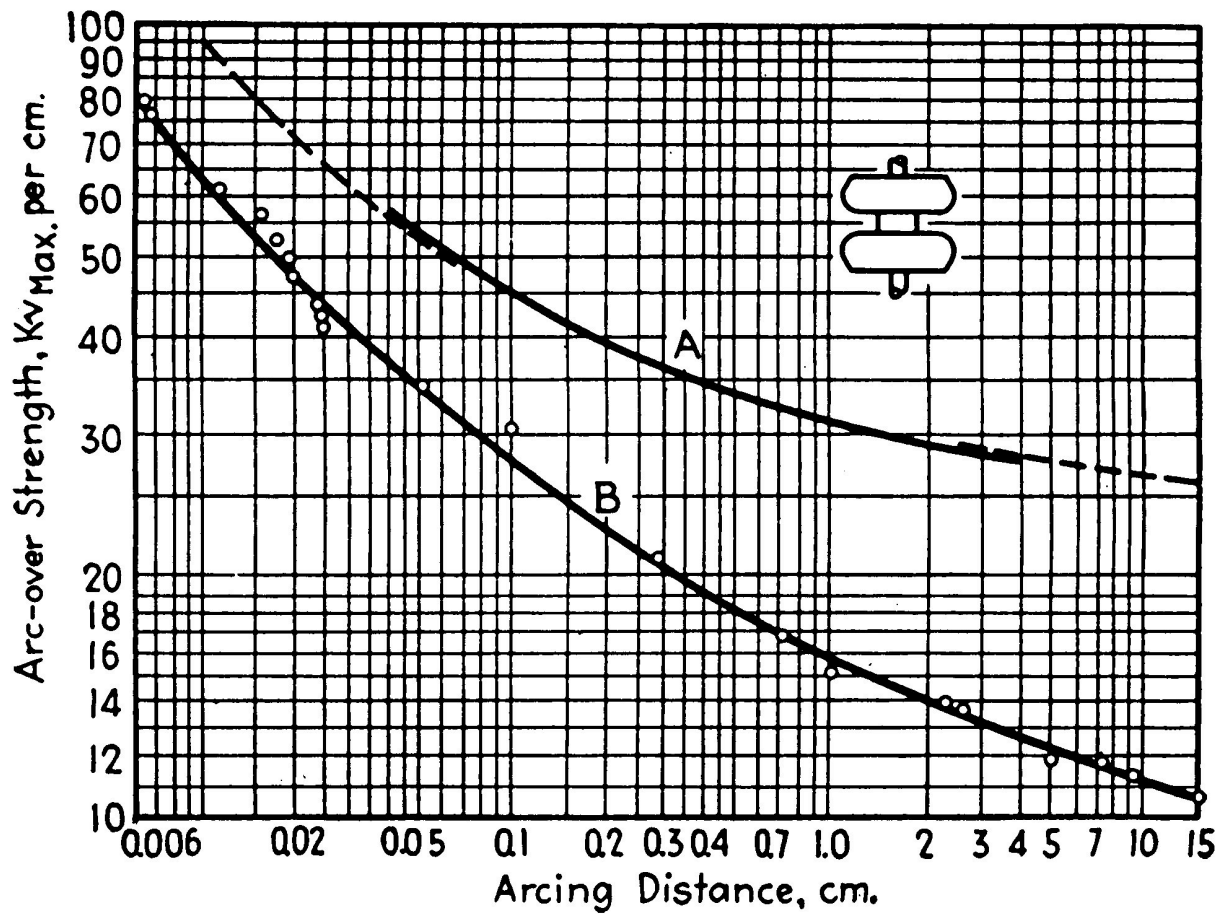
T. Ono, et al., "Micro-discharge and electric breakdown in a micro-gap," Journal of Micromechanics and Microengineering, 2000. 10(3): pp. 445-451.

J.-M. Torres, et al., "Electric field breakdown at micrometre separations," Nanotechnology, 1999. 10(1): pp. 102-107.

R.S. Dhariwal, et al., "Breakdown electric field strength between small electrode spacings in air," In: Micro Systems Technologies '94. 1994. Berlin: VDE-Verlag GmbH.

based on an email from Ralf G. Longwitz (Swiss Fed. Inst. of Technology)

Surface flashover along an insulating standoff (from Cobine, Dover. 1958, p. 166)



Curve A: air breakdown voltage versus spacing

Curve B: flashover in the same structure with a glass cylinder spacer

Both at 20° C, 760 mm Hg, 60 Hz)