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ECE695: Reliability Physics of Nano-Transistors

Lecture 29: Breakdown of Thick Dielectrics – Part 1

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Outline

1) Introduction

2) Breakdown in gas dielectric and Paschen's law

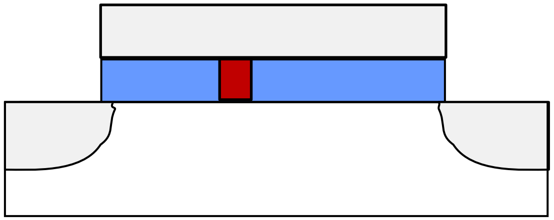
3) Spatial and temporal dynamics during breakdown

4) Breakdown in bulk oxides: puzzle

5) Conclusions

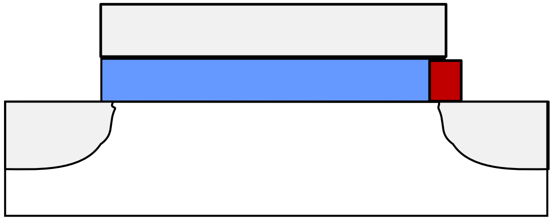
Lecture outline for dielectric breakdown

Lecture 21-26

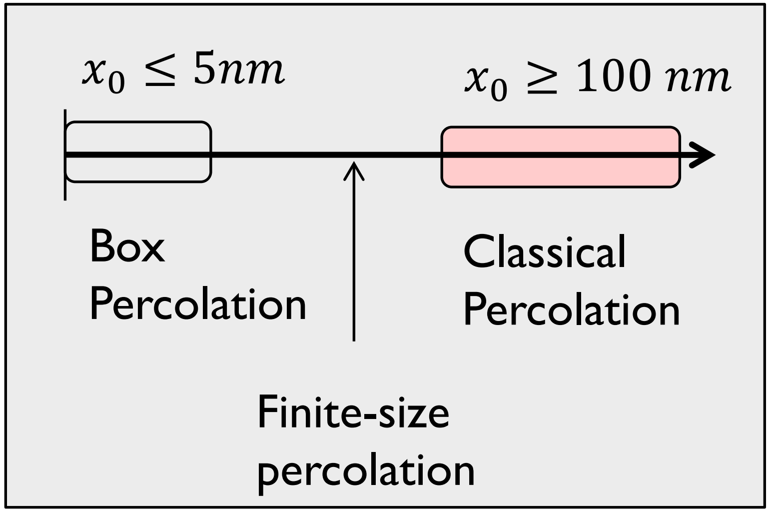


Uncorrelated SBD in thin oxides

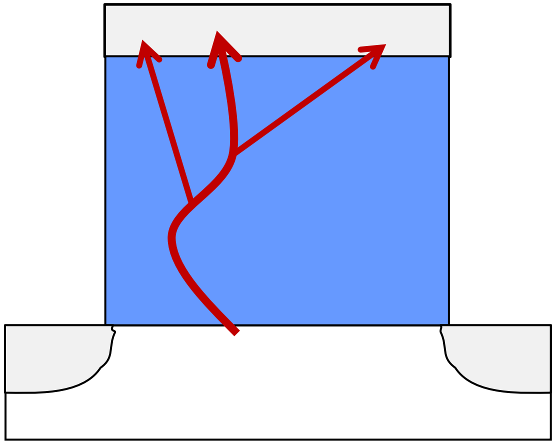
Lectures 27-28



Correlated BD in thin oxides

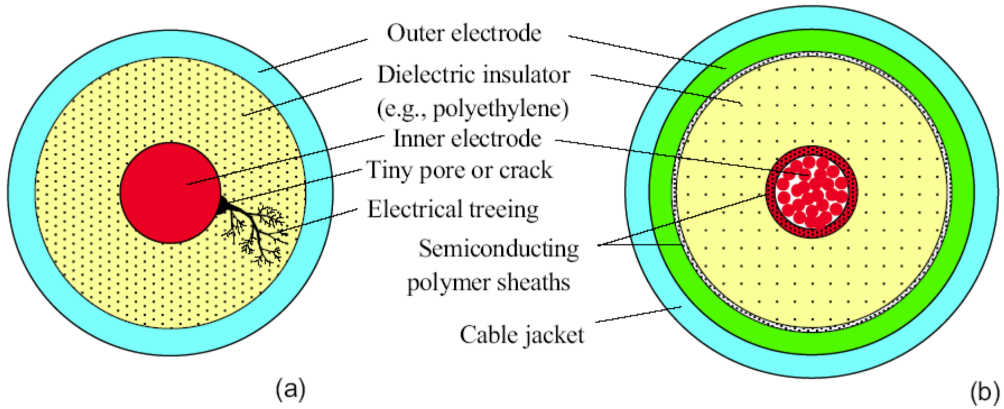


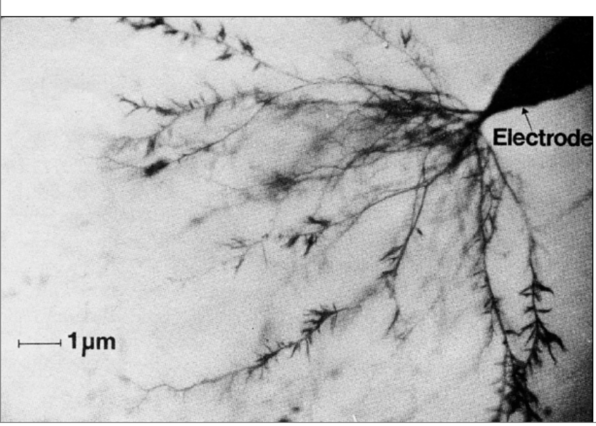
Lectures 29-30



Correlated BD in thick oxides

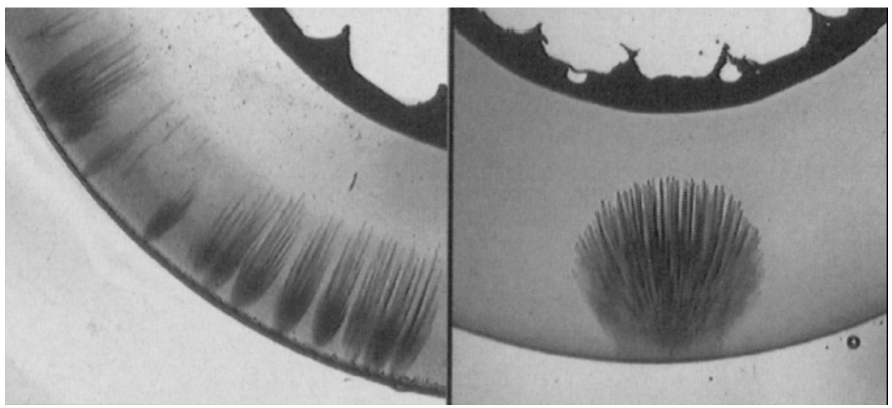
Breakdown in thick dielectrics: water tree





Electrical breakdown by *treeing* (formation of discharge channels) in a low-density polyethylene insulation when a 50 Hz, 20 kV (rms) voltage is applied for 200 minutes to an electrode embedded in the insulation.

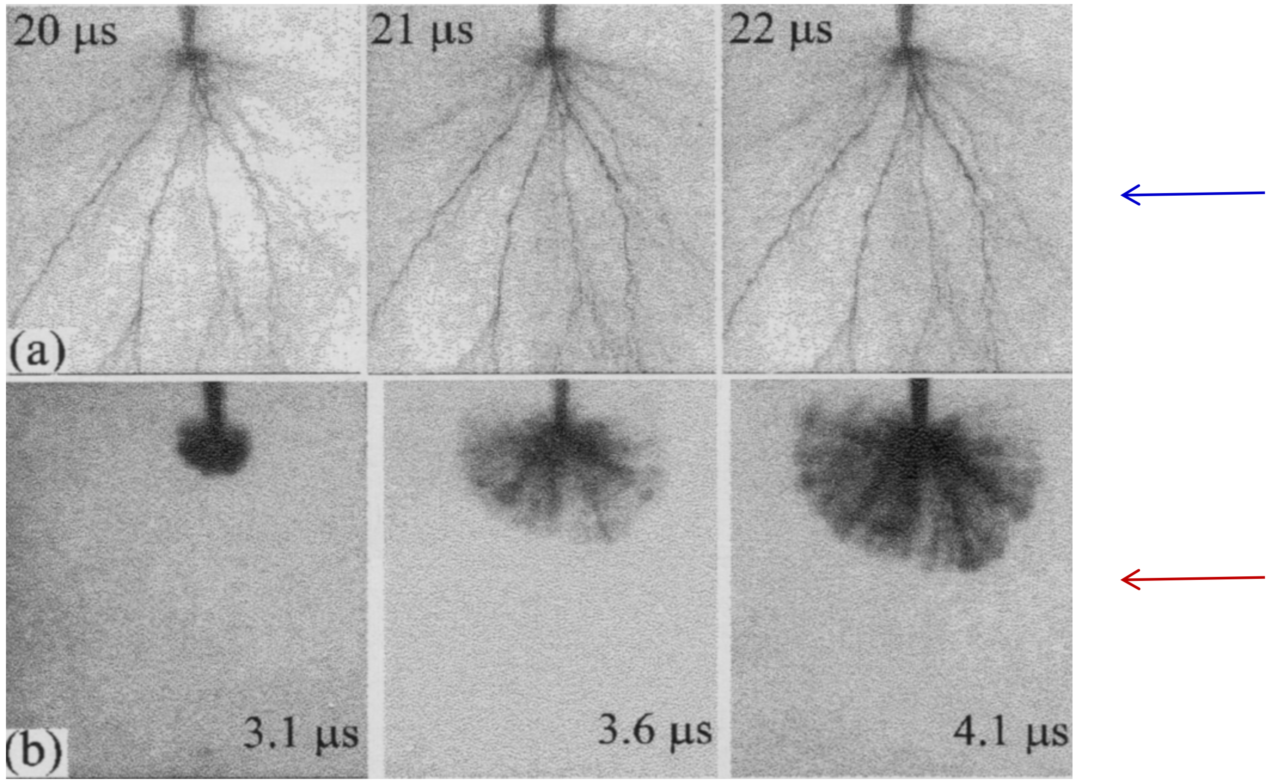
SOURCE: J. W. Billing and D. J. Groves, *Proceedings of the Institution of Electrical Engineers*, **212**, 1974, p. 1451.



Breakdown in thick dielectrics

Coaxial cable connector with traces of corona discharge; electrical treeing. SOURCE: M. Mayer and G.H. Schröder ,"Coaxial 30 kV Connectors for the RG220/U Cable: 20 Years of Operational Experience"IEEE Electrical Insulation Magazine ,Vol. 16, March/April 2000, p. 11, Figure 6. (© IEEE, 2000)

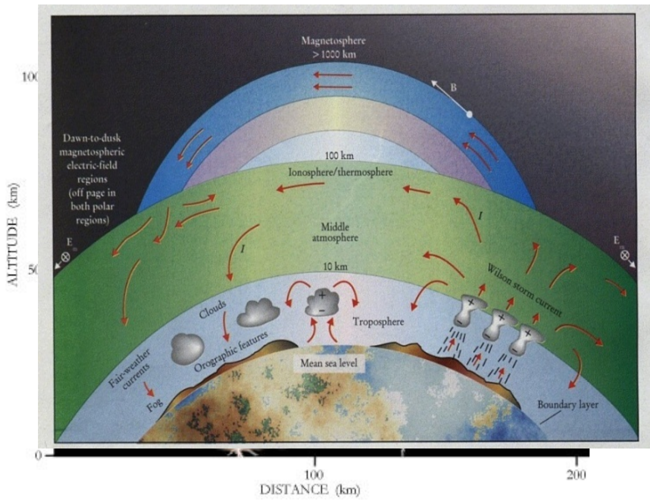
Breakdown in thick dielectrics



Tree and bush type electrical discharge structures
(a) Voltage, V = 160 kV, gap spacing d = 0.06 m at various times.
(b) Dense bush discharge structure, V = 300 kV, d = 0.06 m at various times.
SOURCE: V. Lopatin, M.D. Noskov, R. Badent, K. Kist, A.J. Swab, "Positive Discharge Development in Insulating Oil: Optical Observation and Simulation" IEEE Trans. on Dielec and Elec. Insulation Vol. 5, No. 2, 1998, p. 251, Figure 2. (© IEEE, 1998)

Dielectric breakdown in everyday life

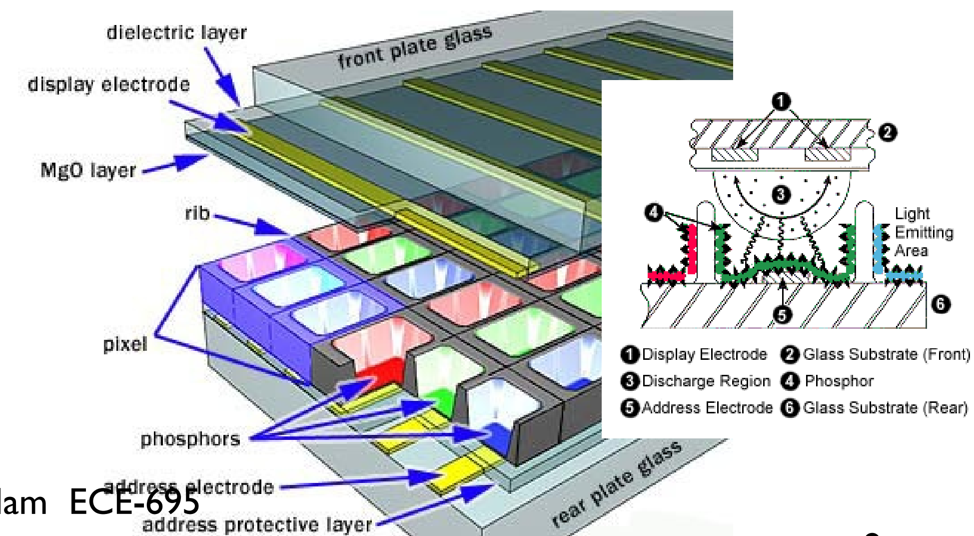
Lightning



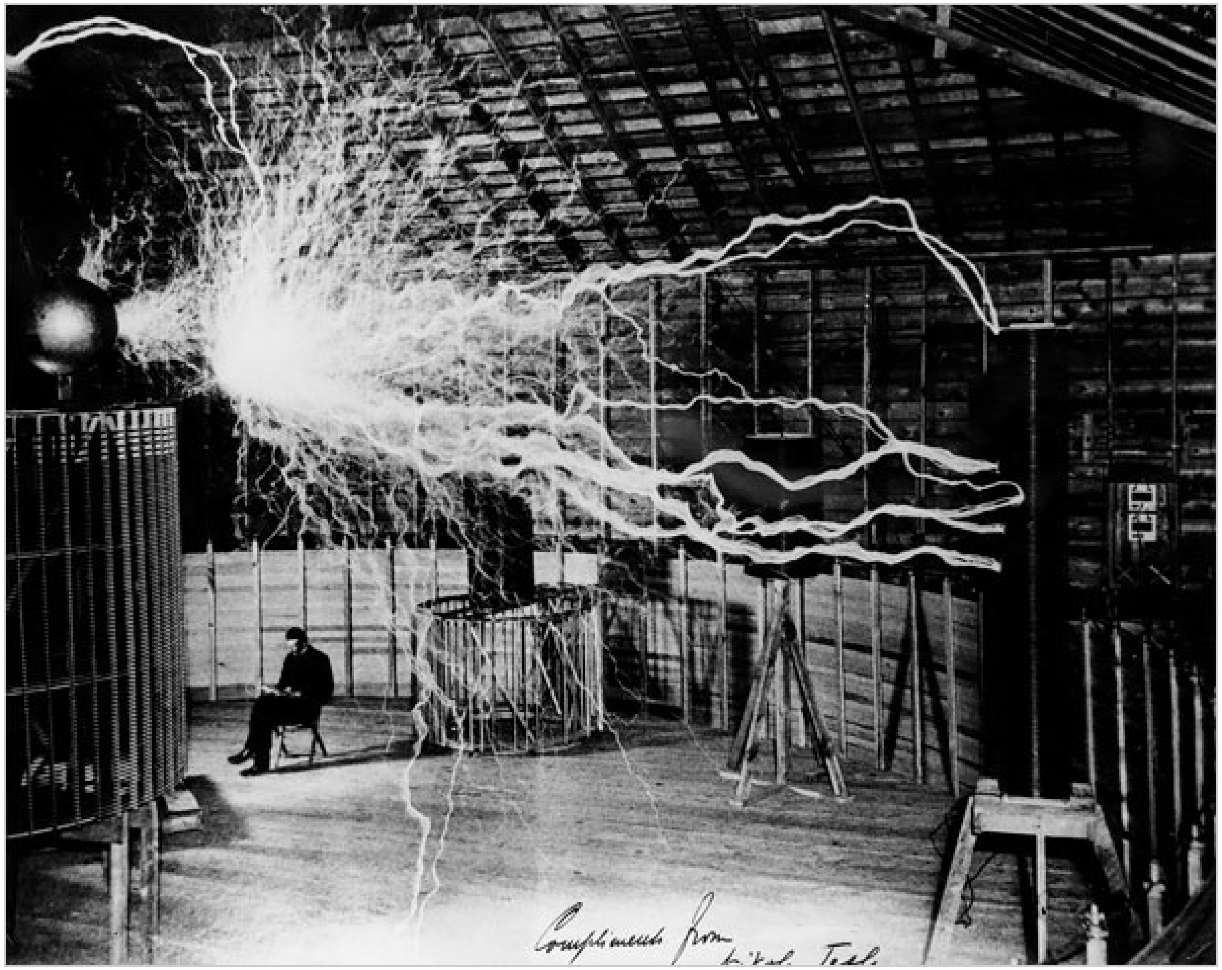
Unrolling a scotch tape

Putterman, Nature, 2008

Plasma TV

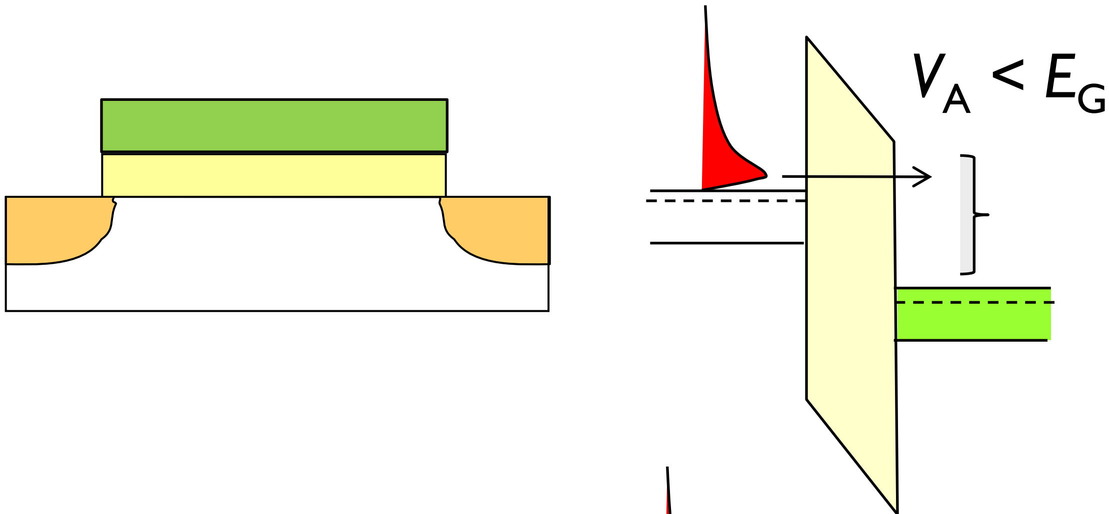


Tesla coils …



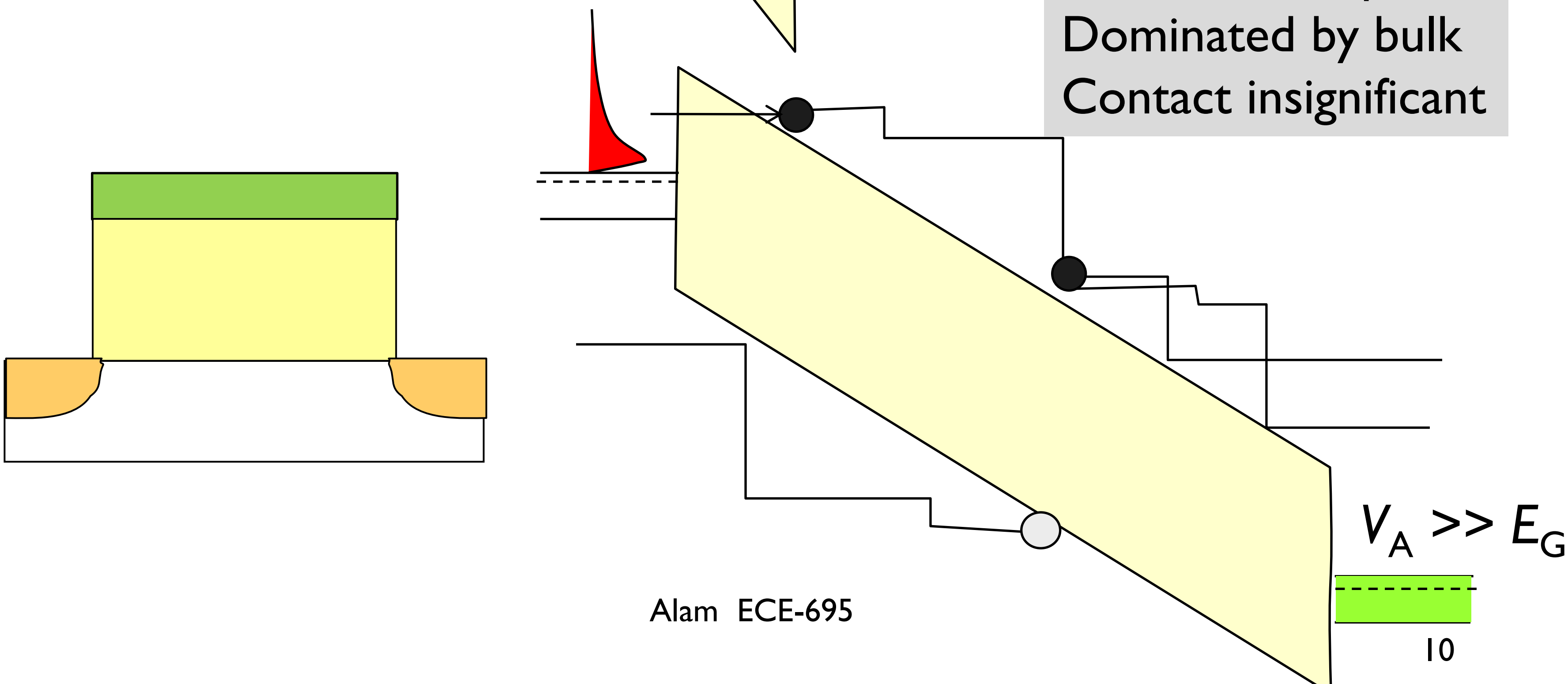
Wireless telegraph, Global power distribution

Breakdown in thick vs. thin oxides



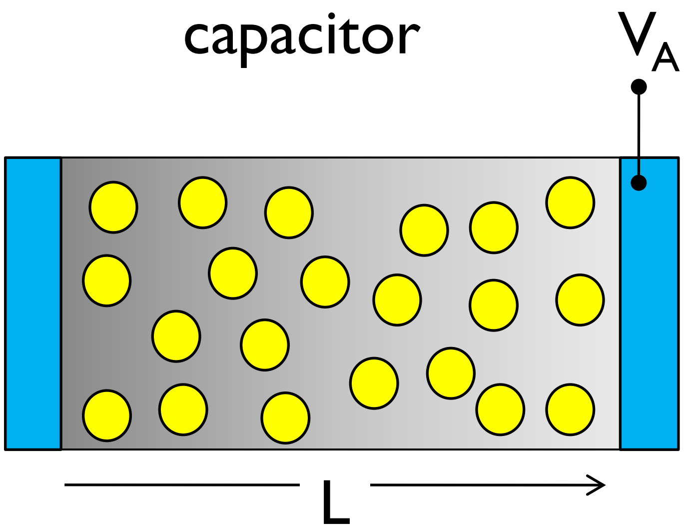
Ballistic transport
Hot contact
Contact dictates BD

Diffusive transport
Dominated by bulk
Contact insignificant

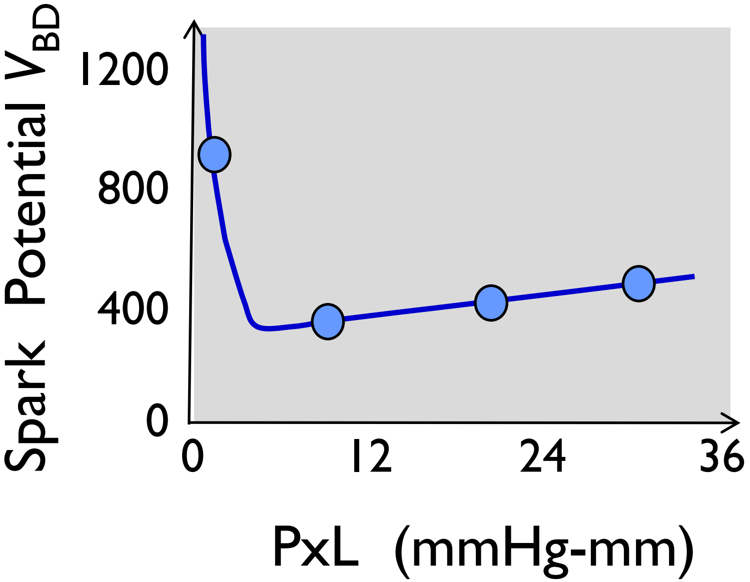


Paschen's law (experiment)

Plane parallel capacitor



$$V_{BD} = \frac{a(P \times L)}{\ln(P \times L) + c}$$



Many gases show this breakdown behavior ….

Outline

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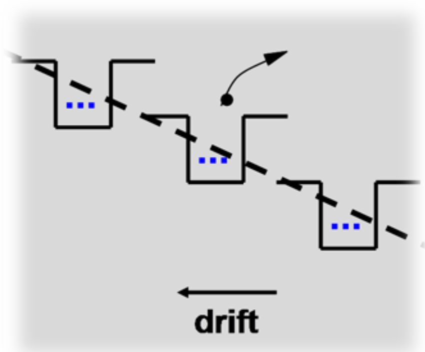
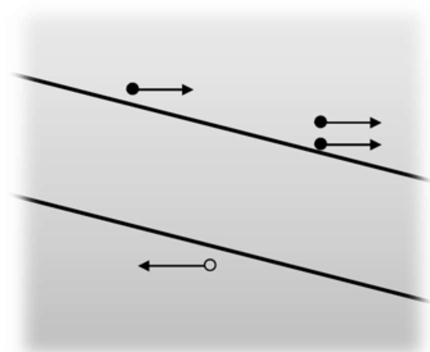
5) Conclusions

Stages of ionization and breakdown

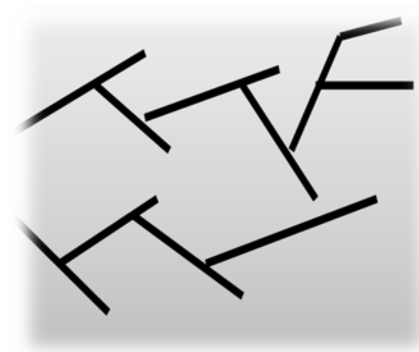
1. Field Ionization

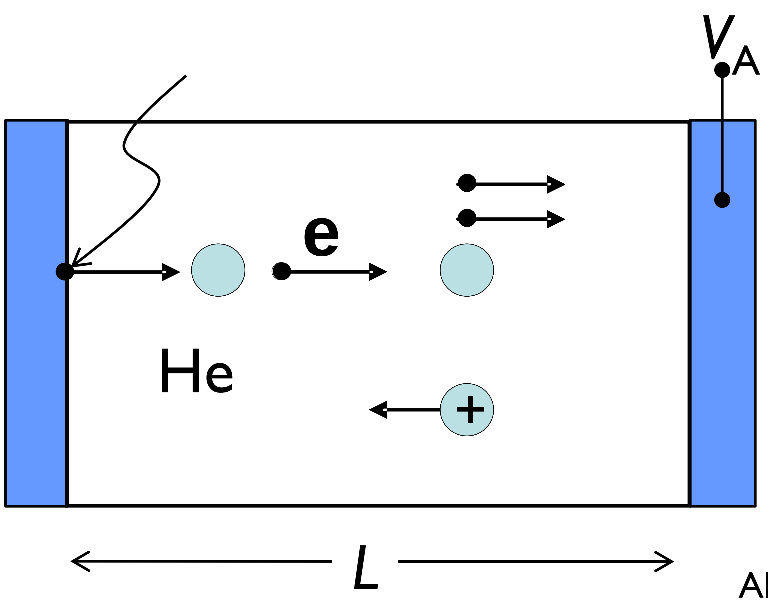


2. Avalanche

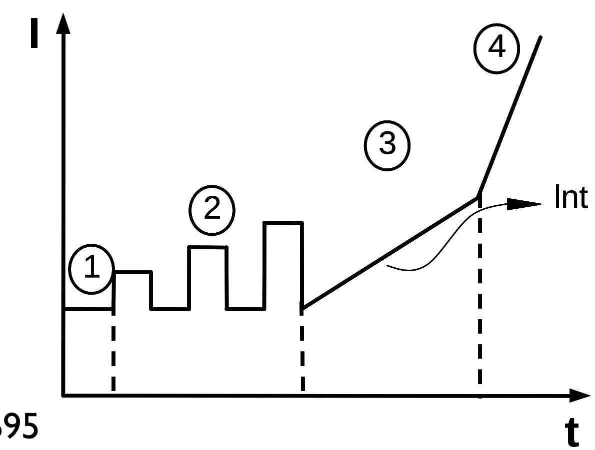


3. Spatial Dynamics





4. Time Signatures



(1) Basics of field ionization

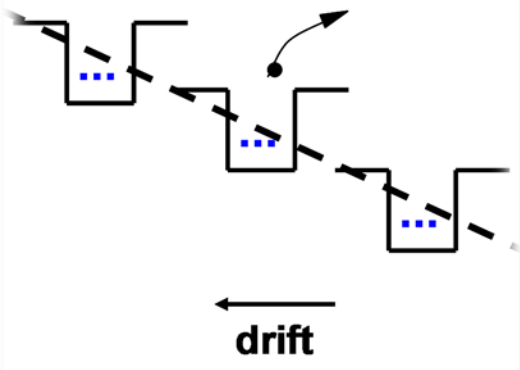
Energy flux balance …

$$q\mathrm{E}\upsilon = \frac{\mathcal{E} - \mathcal{E}_0}{\tau} \qquad \langle \mathcal{E} - \mathcal{E}_o \rangle \approx \langle \mathcal{E} \rangle = q\mathrm{E} \times \upsilon\tau \equiv q\mathrm{E} \times \lambda$$

Energy balance …

$$\langle \mathcal{E} \rangle = \frac{3}{2} k_B T_e + \frac{1}{2} m^2 \upsilon^2 \approx \frac{3}{2} k_B T_e$$

$$\langle \mathcal{E} \rangle = q\mathrm{E}\lambda = 3 k_B T_e / 2$$



Ionization/Length ….

$$\alpha \sim \overbrace{N}^{p_c} \times \overbrace{e^{-\mathcal{E}_0 / k_B T_e}}^{p_e} \sim N \times e^{-3\mathcal{E}_0 / 2q\mathrm{E}\lambda}$$

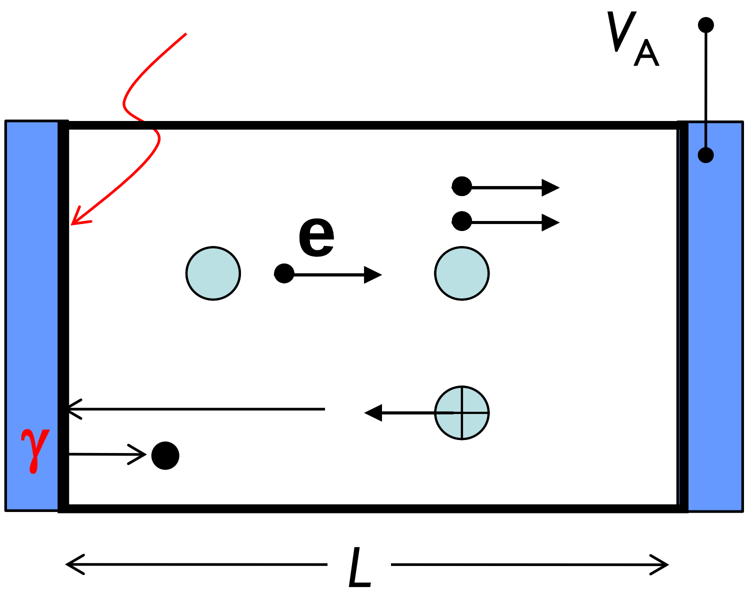
(2) Avalanche: initiation

$$\frac{dn}{dx} = \alpha n \quad n(x) = n_0 e^{\alpha L} + \gamma \left[n_0 \left(e^{\alpha L} - 1 \right) \right] e^{\alpha L} + ...$$

+ve ion

Cathode factor

$$= \frac{n_0 e^{\alpha L}}{1 - \gamma \left(e^{\alpha L} - 1 \right)}$$



At breakdown, even noise is amplified to runaway condition ….
The numerator diverges …

$$\ln\left(1 + \frac{1}{\gamma}\right) \sim \alpha_{BD} L$$

γ depends on geometry …

(2) Avalanche: breakdown voltage

Ionization coefficient and pressure ....

$$\alpha_{BD} \sim \overbrace{N}^{p_c} \times \overbrace{e^{-3E_{0,i}/2q\mathcal{E}_{BD}\lambda}}^{p_e} \sim B_i P \times e^{-A_i P(L/V_{BD})}$$

and breakdown condition …

$$\ln\left(1+\frac{1}{\gamma}\right) \sim \alpha_{BD} L = B_i P \times e^{-A_i P(L/V_{BD})} L$$

Implies Paschen's law …

$$V_{BD} = \frac{A_i P \times L}{\ln(B_i P \times L) - \ln\left\{\ln\left(1+\gamma^{-1}\right)\right\}}$$

$$V_{BD} = \frac{a(P \times L)}{\ln(P \times L) + c}$$

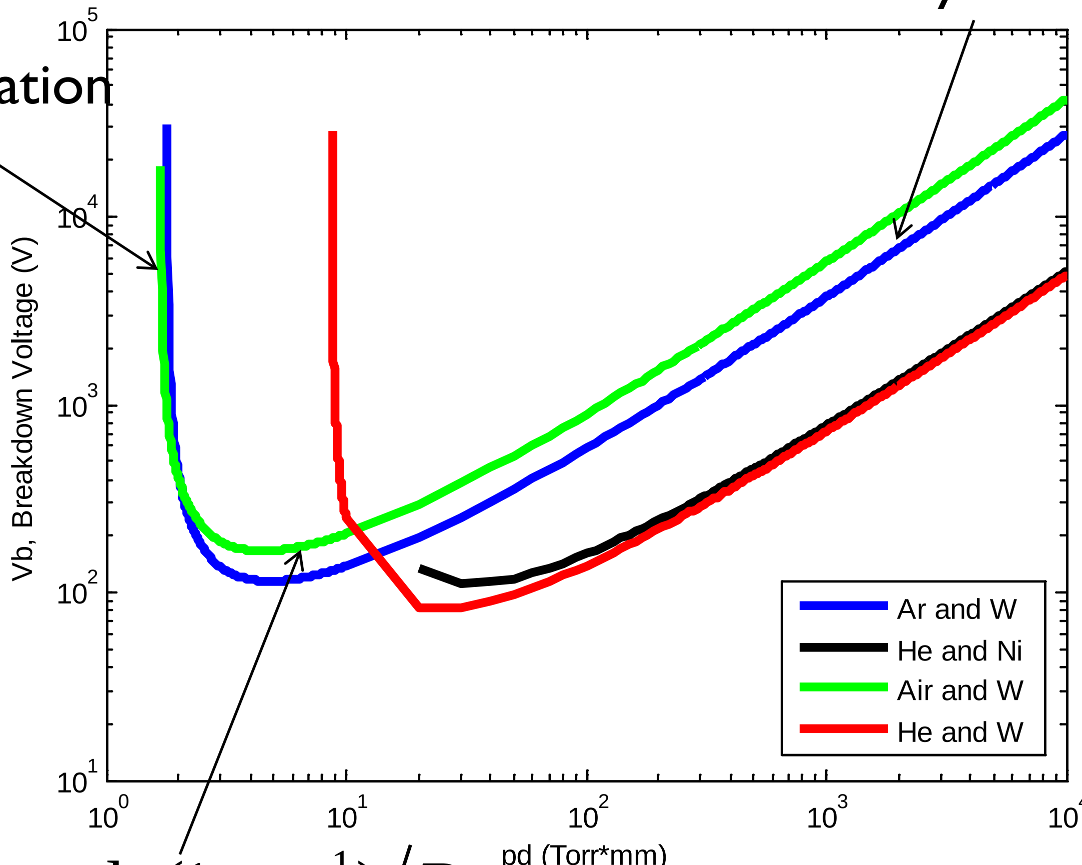
(2) Paschen's law (experiment)

$$V_{\mathrm{BD}} = \frac{a(P \times L)}{\ln(P \times L) + c}$$

a and c material constants

Too many collisions

Insignificant ionization



$$(P \times L)_{\min} = e\ln(1 + \gamma^{-1})/B$$

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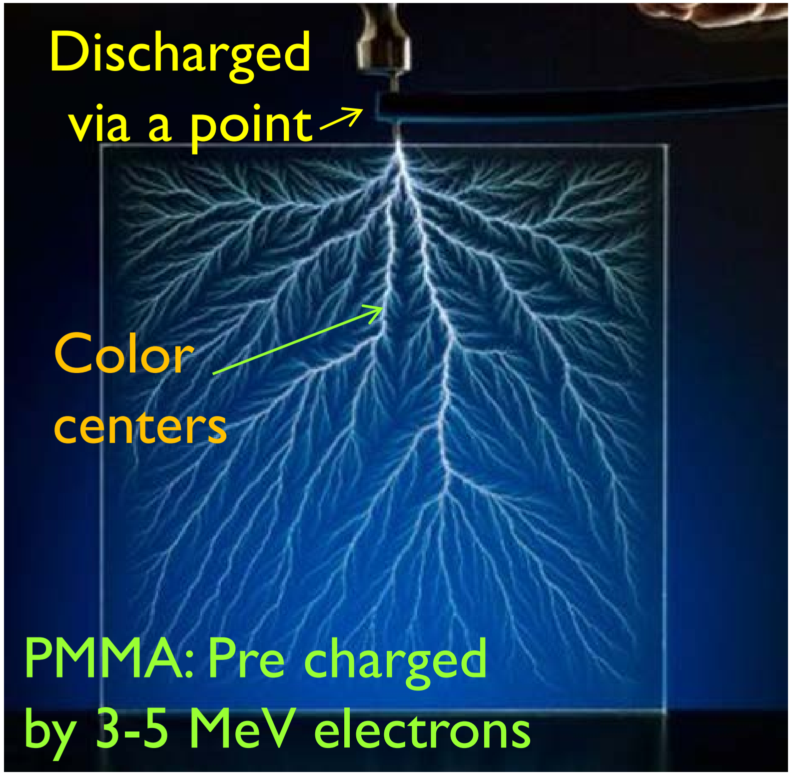
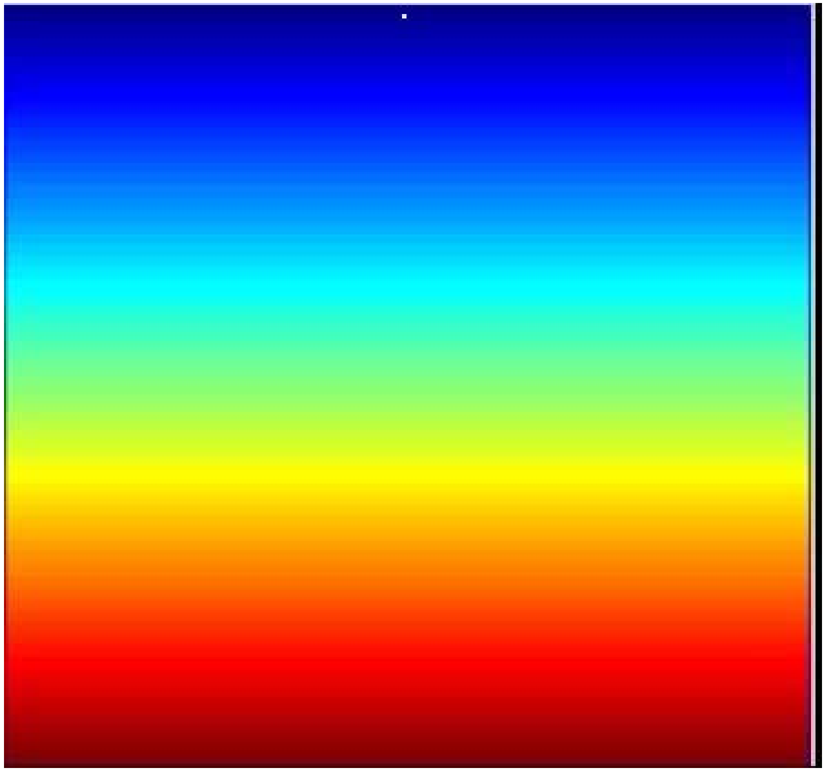
(stage 3) Spatial dynamics at breakdown

Lichtenberg figures



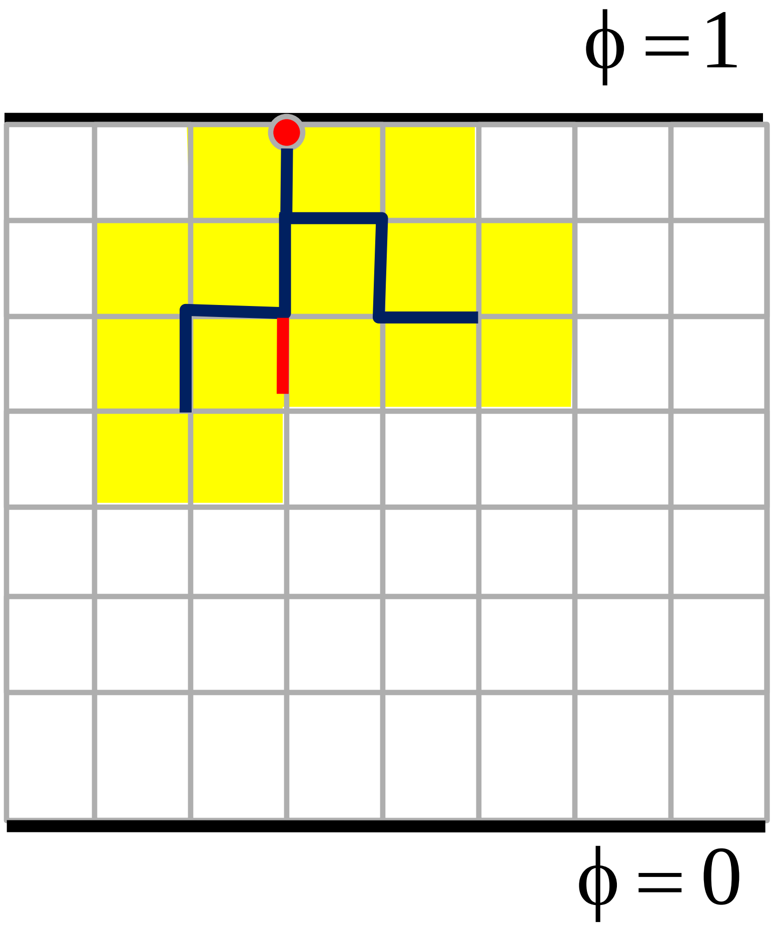
Niemeyer, PRL,52(12), 1984.



Fractal dimension ~ 1.6-1.7

One of the great successes in understanding BD in 1980s …

Algorithm for fractal model of breakdown



- Pattern grows stepwise
- ϕ=0 for all discharged points
- Solve Poisson equation at every time-step
- One step is selected at each step

$$P(i,k \rightarrow i',k') = \frac{E(i',k')}{\sum E}$$

Repeat

Niemeyer, PRL,52(12), 1984.

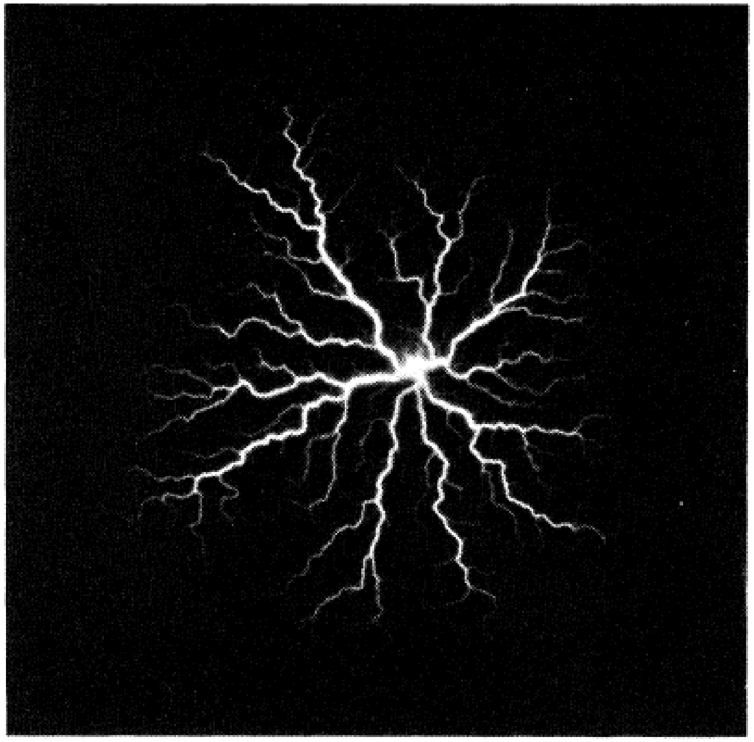


FIG. 1. Time-integrated photograph of a surface leader discharge (Lichtenberg figure) on a 2-mm glass plate in 0.3-MPa SF_6. Applied voltage pulse: 30 kV × 1 μs (Ref. 5). This experiment corresponds to an equipotential channel system growing in a plane with radial electrode.

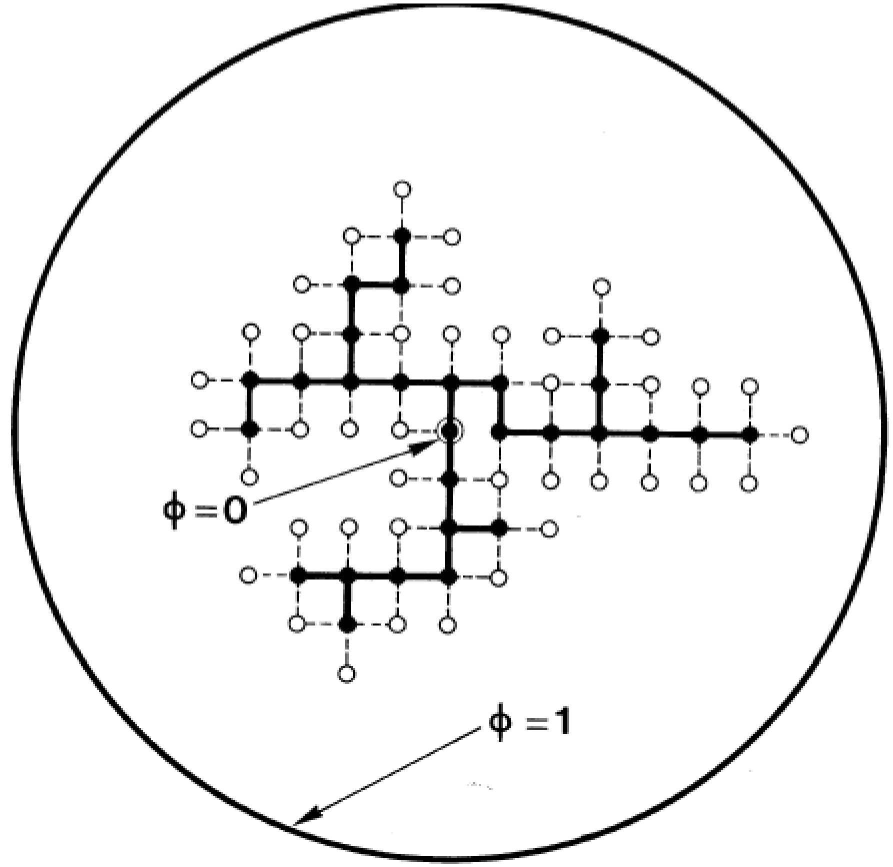
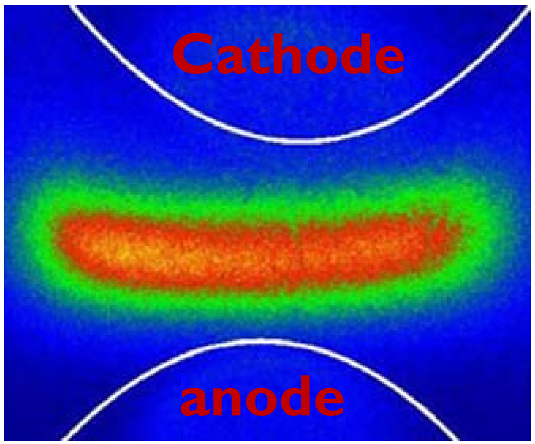


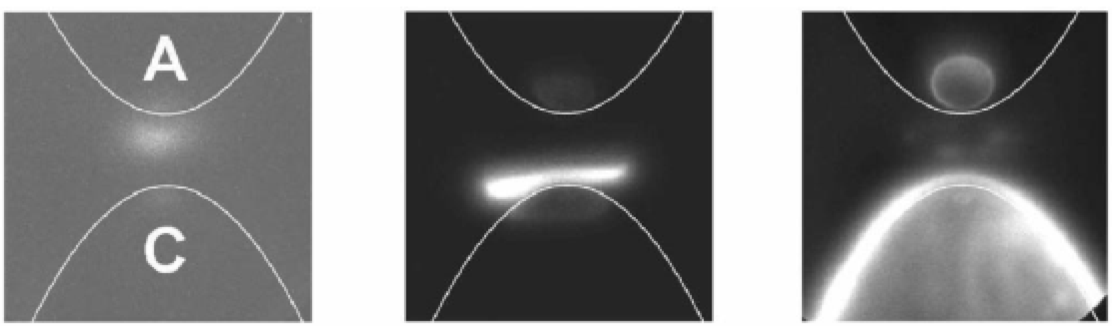
FIG. 2. Illustration of the stochastic model we introduce to simulate dielectric breakdown on a lattice. The central point represents one of the electrodes while the other electrode is modeled as a circle at large enough distance. The discharge pattern is indicated by the black dots connected with thick lines and it is considered equipotential ($\phi = 0$). The dashed bonds indicate all the possible growth processes. The probability for each of these processes is proportional to the local electric field (see text).

Niemeyer, PRL,52(12), 1984.

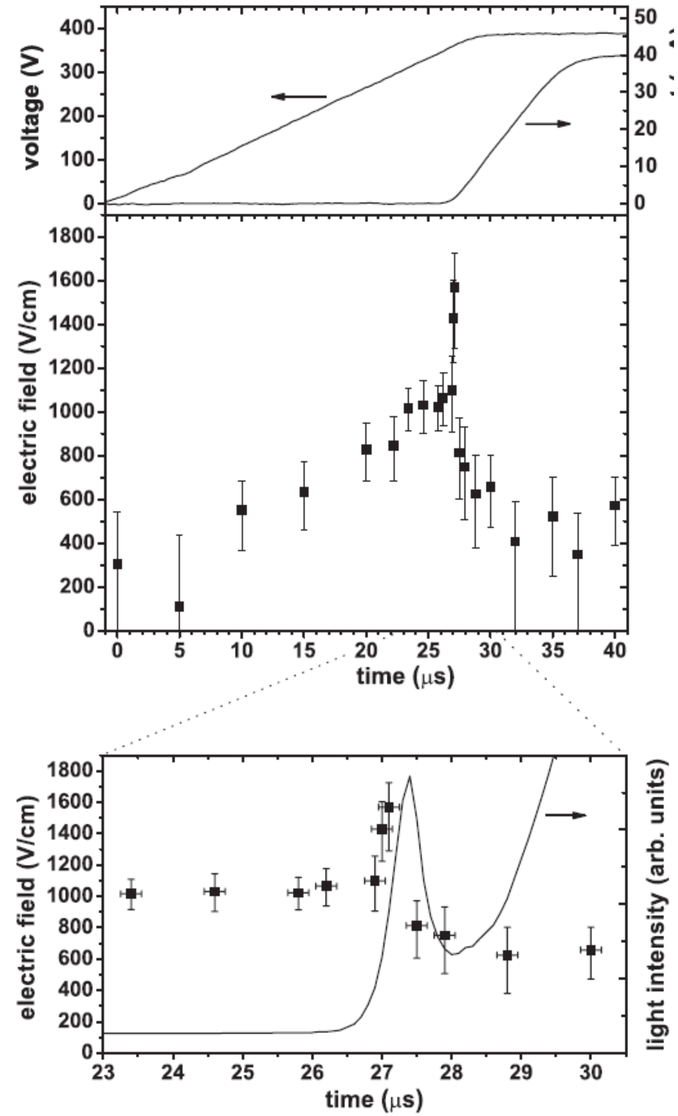
(4) Temporal dynamics of breakdown



Xenon gas discharge

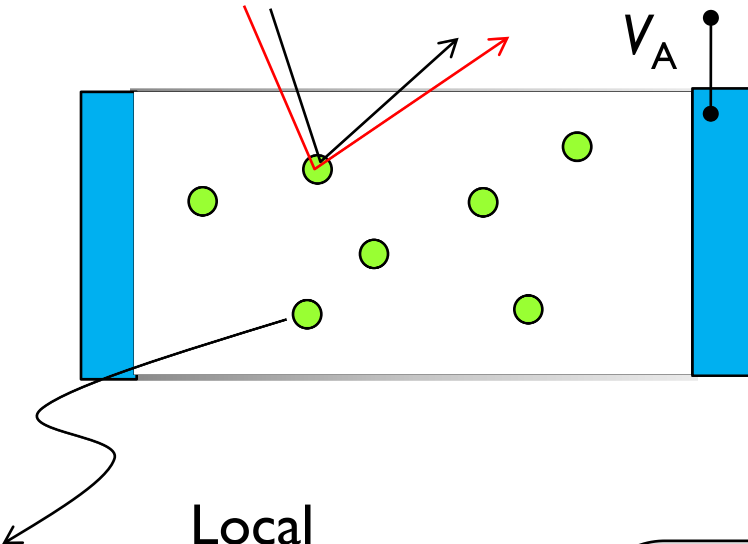


t = 26.0 μs　t = 27.5 μs　t = 40.0 μs

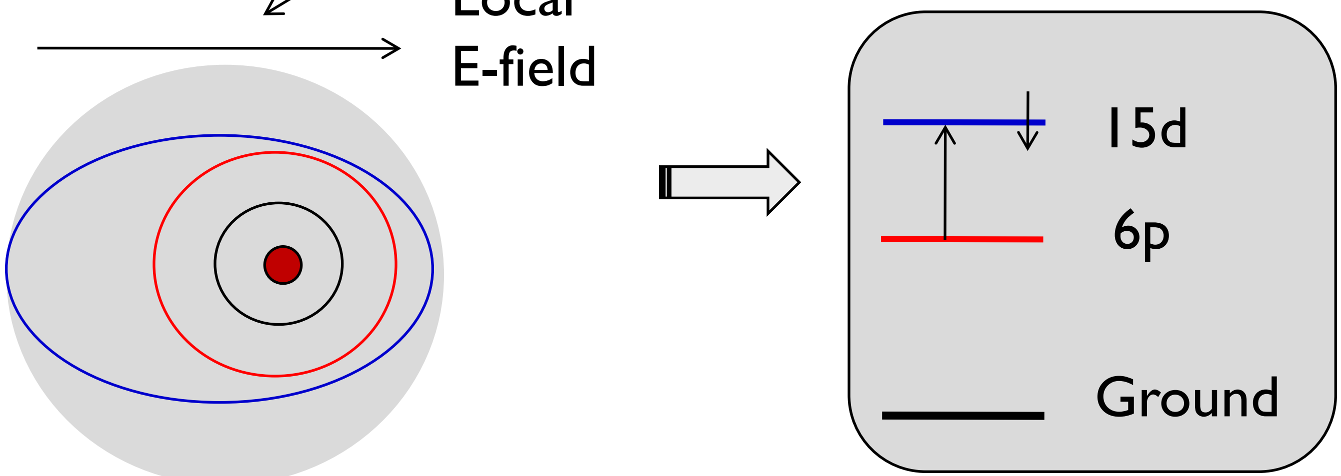


Wagenaars et al., PRL, 98, 075002, 2007. Alam ECE-695

(4) Temporal dynamics by Stark spectroscopy



Wagenaars et al., PRL, 98, 075002, 2007.



Stark shifts define E-field

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Breakdown in bulk solid dielectric

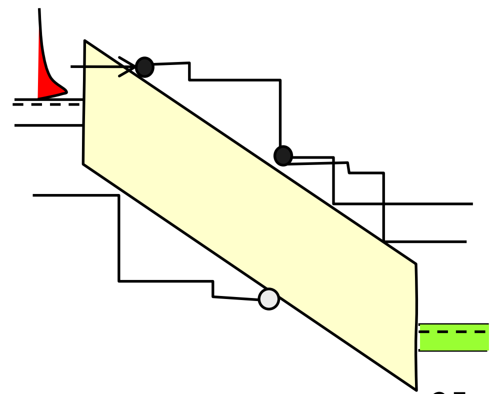
Momentum balance …

$$\frac{m^* \upsilon}{\tau} = q\mathrm{E} \Rightarrow \upsilon = \frac{q\mathrm{E}\tau}{m^*}$$

Energy balance …

$$q\mathrm{E}\upsilon = \frac{\mathcal{E} - \mathcal{E}_0}{\tau} \approx \frac{\hbar\omega_0}{\tau}$$

$$\upsilon \approx \sqrt{\frac{\hbar\omega_0}{m^*}}$$



$$\mathrm{E} \approx \frac{\hbar\omega_0}{q\upsilon\tau} = \frac{\sqrt{\hbar\omega_0 m^*}}{q\tau}$$

$$\frac{1}{\tau} \sim m^{*3/2}\sqrt{\mathrm{E}}$$

Ionization/per atom/length ….

Hole generation condition …

$$\frac{V_{\mathrm{BD}}}{L} \equiv \mathrm{E}_{\mathrm{BD}}^{II} = \frac{\sqrt{\hbar\omega_0}\, m^{*2}}{q} \sim \sqrt{\mathcal{E}_G}$$

Theory vs. experiment: small bandgap solids

1) *J.M. Meek and D.J. Craggs, Electrical Breakdown of Gases (Oxford U.P., London, 1953)*
2) *S.M. Sze, Physics of Semiconducting Devices (Wiley, New York, 1969)*

Materials	$\mathcal{E}_G$ (eV)	m^*/m_o	$\hbar\omega_o$ (eV)	E_B (predicted)	E_B (observed)	Reference
InSb	0.17	0.013	0.025	2.5×10^2	4×10^2	(1)
InAs	0.36	0.02	0.03	8.6×10^2	1×10^3	(1)
Ge	0.66	0.22	0.037	…	1×10^5	(2)
Si	1.12	0.32	0.063	3.7×10^5	3×10^5	(2)
GaAs	1.43	0.35	0.035	3.7×10^5	3×10^5 $\sim5\times10^5$	(2) (1)
GaP	2.24	0.35	0.05	5.5×10^5	5×10^5 $\sim10\times10^5$	(2) (1)

Reasonable correspondence between theory and experiments for low-gap relatively clean materials.

Theory vs. experiment: large bandgap solids

1) *J.M. Meek and D.J. Craggs, Electrical Breakdown of Gases (Oxford U.P., London, 1953)*
2) *M. Lenzlinger and E.H. Snow, J. Appl. Phys. (40, 287) (1969)*
3) *C.M. Osburn and E.J. Weitzmann, J. Electrochem. Soc. (119, 603) (1972)*

		Acoustic Phonons			Optical Phonons	
Materials	$\mathcal{E}_G$ (eV)	E_B (predicted)	E_B (observed)	**Reference**	$\hbar\omega_o$ (eV)	E_B (predicted)
CdS	2.5	1.7×10^7	2×10^6	(1)	0.038	4.1×10^6
ZnSe	2.6	1.7×10^7	2×10^6	(1)	0.03	3.6×10^6
ZnO	3.3	2.2×10^7	4×10^6	(1)	0.07	6.4×10^6
SiO_2	9.0	6.1×10^7	9×10^6	(2,3)	0.12	1.4×10^7
NaCl	8.0	5.5×10^7	1.6×10^6	(1)	0.024	6.2×10^6

Poorer correspondence between theory and experiments for very larger-gap materials ….

Conclusions

- ❑ Dielectric breakdown has a long history and broad range of physical and technological applications

- ❑ TDDB is important for thick and thin dielectrics, but the physics of breakdown is very different.

- ❑ Correlated breakdown in thick dielectric could be understood in terms of Paschen's model – although the spatial and temporal details requires generalizations.

- ❑ While the model is excellent for small bandgap semiconductors, large bandgap materials often require assumption of pre-existing defects.

References

- The first observation of water-treeing was reported by T. Miyashite in "Detoriation of water-immersed polyetheline coated wire by treeing," Proc. of IEEE-NEMA EI conference, pp. 131-135, 1969. R. Ross and J. J. Smit offers a plausible theory in IEEE TEI, 27, p. 519, 1992. For a good review of water-treeing, see J. Xu and S.A. Boggs, IEEE Ins. Mag. 10(5), 29, 1994.
- The Paschen law is discussed in detail in "Simulation of ion generation and breakdown in atmospheric air", W. Zhang, T. S. Fisher,a) and S.V. Garimella, JAP, 96(11), 6006, 2004.
- The original theory of bulk breakdown is due to A.Von Hippel, Electric Breakdown in Solid and Liquid Insulators", JAP, 8, p. 815, 1938. This was subsequently generalized by many, including B. K. Ridley, "Mechanism of electrical breakdown in SiO2 films", JAP, 46(3), p 998, 1975.
- The percolation theory is discussed in detail in 2009 Summer School Lectures on "Nanostructured Electronic Devices: Percolation and Reliability" "http://nanohub.org/resources/7168
- A book that connects fracture and percolation in a very systematic way is "Statistical Physics of Fracture and Breakdown in Disordered System", B. Chakrabarti, and L. Gilles Benguigui, Clarendon Press, Oxford, 1997.
- L. Niemeyer, L. Pietronero, and H. J. Wiesmann, Fractal Dimension of Dielectric Breakdown, PRL, 52(12), p 1033, 1984.
- The theory of negative pressure is discussed in "Physics for Scientists and Engineers", by D. C. Giancoli, 2nd Edition, Vol. 1, Prentice Hall. Page. 303.

Review Questions

1. Mention a few differences between thick and thin oxide breakdown.
2. Is breakdown in thick oxides contact dominated? Can I use AHI theory here?
3. How does the Paschen's cascade initiate?
4. What does it mean to have a fractal dimension of 1.7 for 2D breakdown? Why does the number suggest spatial correlation ?
5. What is a color center? How does color center help us visualize breakdown in polymers?
6. Explain physically the origin of the minimum breakdown voltage for gas dielectric?
7. Is gas dielectric breakdown reversible? What about solid dielectric BD?