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ECE695: Reliability Physics of Nano-Transistors
Lecture 30: Breakdown in Dielectrics with Defects

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Outline

1) Introduction
2) Theory of pre-existing defects: Thin oxides
3) Theory of pre-existing defects: thick oxides
4) Conclusions

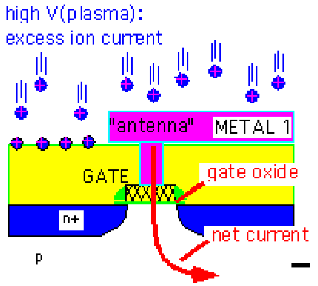
Theory vs. experiment: large bandgap solids

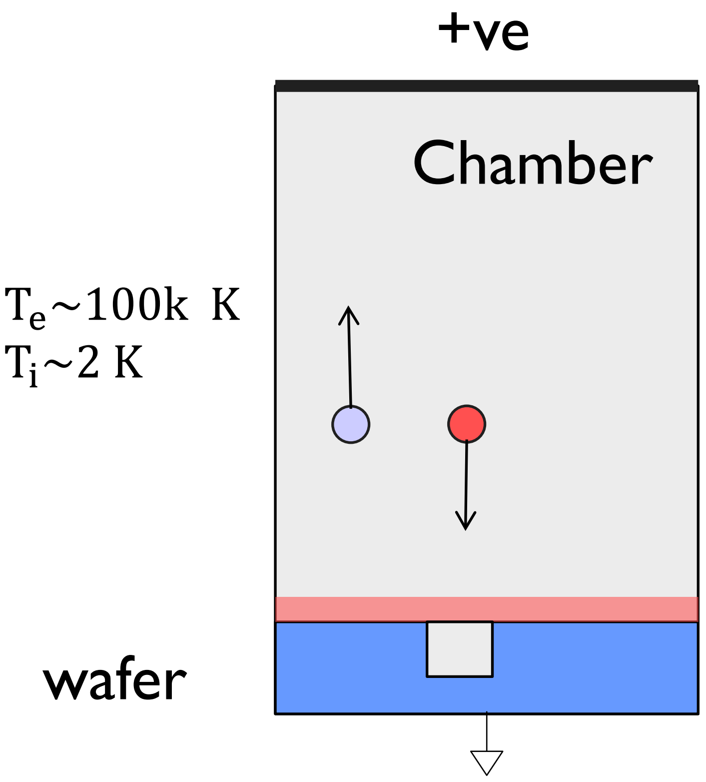
1) *J.M. Meek and D.J. Craggs, Electrical Breakdown of Gases (Oxford U.P., London, 1953)*
2) *M. Lenzlinger and E.H. Snow, J. Appl. Phys. (40, 287) (1969)*
3) *C.M. Osburn and E.J. Weitzmann, J. Electrochem. Soc. (119, 603) (1972)*

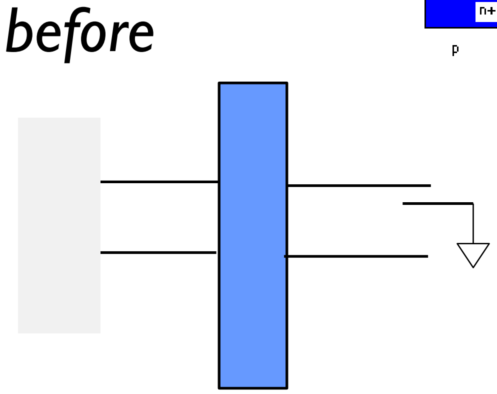
		Acoustic Phonons			**Optical Phonons**	
Materials	**$\mathcal{E}_G$ (eV)**	**E_B (predicted)**	**E_B (observed)**	**Reference**	**$\hbar\omega_o$ (eV)**	**E_B (predicted)**
CdS	2.5	1.7×10^7	2×10^6	(1)	0.038	4.1×10^6
ZnSe	2.6	1.7×10^7	2×10^6	(1)	0.03	3.6×10^6
ZnO	3.3	2.2×10^7	4×10^6	(1)	0.07	6.4×10^6
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

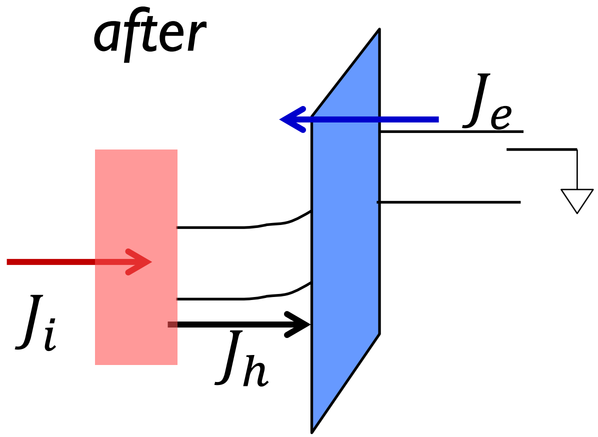
Poor correspondence between theory and experiments for large-gap materials ….

Damaged by plasma etching





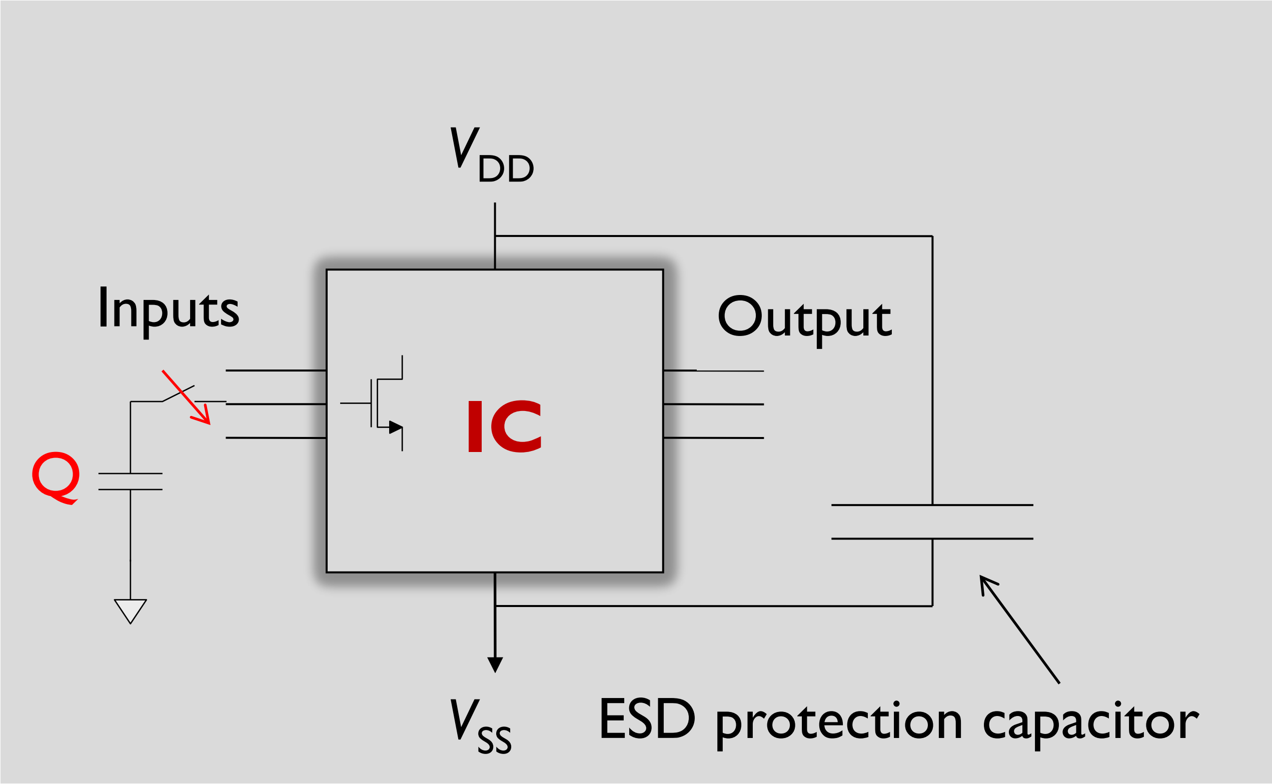




Voltage stresses the oxide and creates the damage

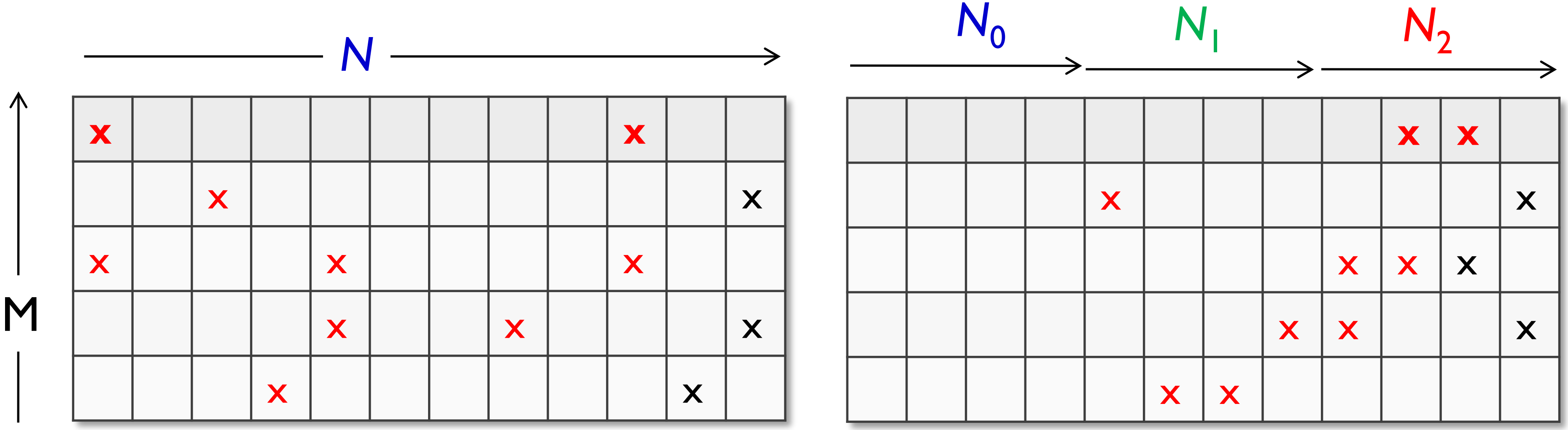
Damage during electrostatic discharge (nonequilibrium pre-existing defects)

Human body or Machine



Similar to plasma charging damage

Breakdown with preexisting defects



$$1-F=(1-F_{\mathrm{m=0}})^{N_0}\,(1-F_{\mathrm{m=1}})^{N_1}\,(1-F_{\mathrm{m=2}})^{N_2}\;\ldots(1-F_{\mathrm{m=M-1}})^{N_{m-1}}$$

$$1-F=(1-q^{M})^{N_0}(1-q^{M-1})^{N_1}(1-q^{M-2})^{N_2}\ldots(1-q^{M-m+1})^{N_{\mathrm{m-1}}}$$

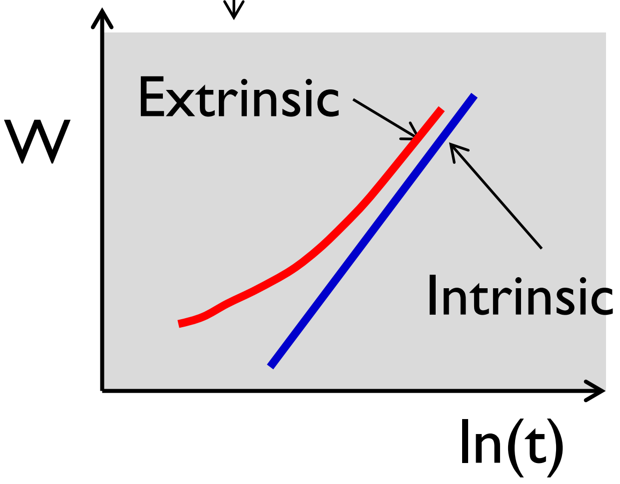
$$-\ln(1-F)=N_0q^{M}+N_1q^{M-1}+N_2q^{M-2}+\ldots.=N_0q^{M}\left[1+\frac{N_1}{N_0}\frac{1}{q}+\ldots.\right]$$

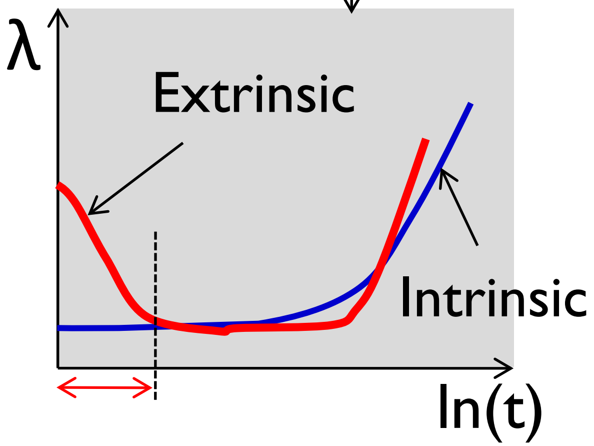
Breakdown with preexisting defects

$$\ln(-\ln(1-F)) = \ln N_0 + M\ln q + \ln[1+\frac{N_1}{N_0}\frac{1}{q}+....] \qquad q = at^{\alpha} = (\frac{t}{\eta_0})^{\alpha}$$

$$\cong \ln N_0 + \beta\ln(\frac{t}{\eta_0}) + \frac{N_1}{N_0}\frac{1}{q} = \ln N_0 + \beta\ln(\frac{t}{\eta_0}) + \frac{N_1}{N_0}(\frac{\eta_0}{t})^{\alpha}$$

$$\lambda \equiv \frac{dF_n / dt}{1-F_n} = (N_0\frac{\beta}{\eta_0^{\beta}})t^{\beta-1}[1+\frac{N_1\eta_0^{\alpha}}{N_0}(\frac{\beta-\alpha}{\beta})\frac{1}{t^{\alpha}}]$$





Infant mortality, burn-in protocol …

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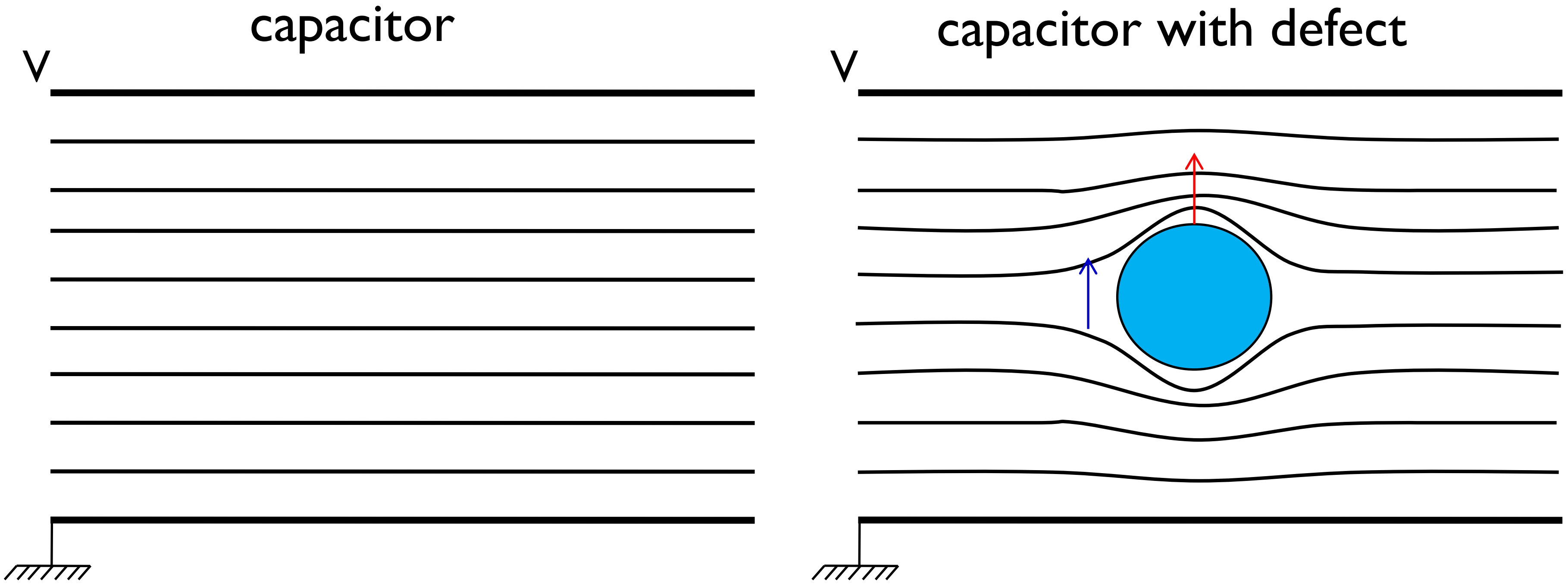
Background: Analogy to Fracture Mechanics

1. Leonardo Vinci experimenting with strength of wires
2. Two sciences by Galileo: One is the fracture strength of Venetian ships
3. WWII – 4700 liberty ships made by welded parts, 1200 damaged, 200 fractured, 10 split in half.
4. Comet disaster due to rivet joint smoves Airline industry from UK to US.

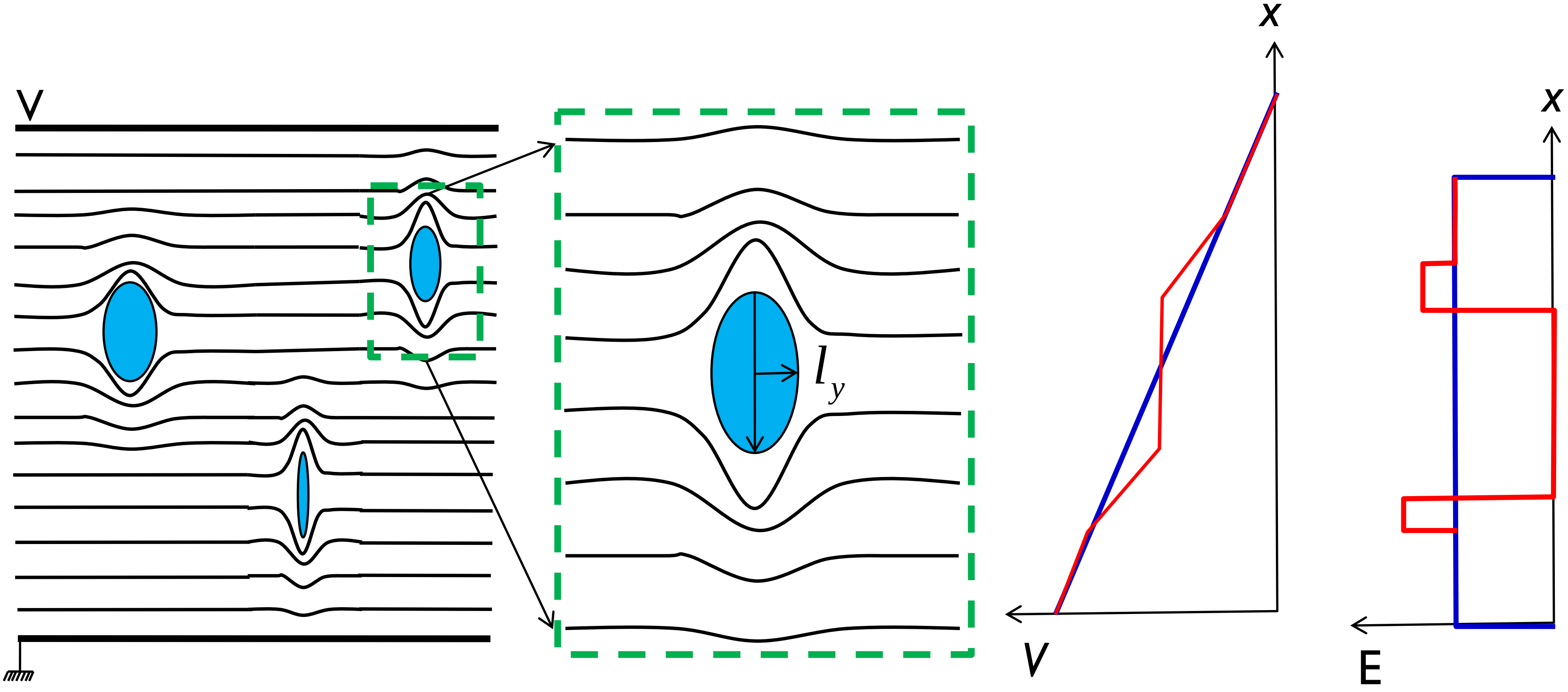
Critical-sized pre-existing defects can lead to dramatic failure in strength of materials

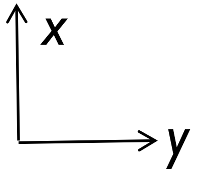
Pre-existing defects, field enhancement, and breakdown in thick insulators (e.g. polymers)



Defects enhances local electric field
and reduces breakdown strength

Defects and fields …



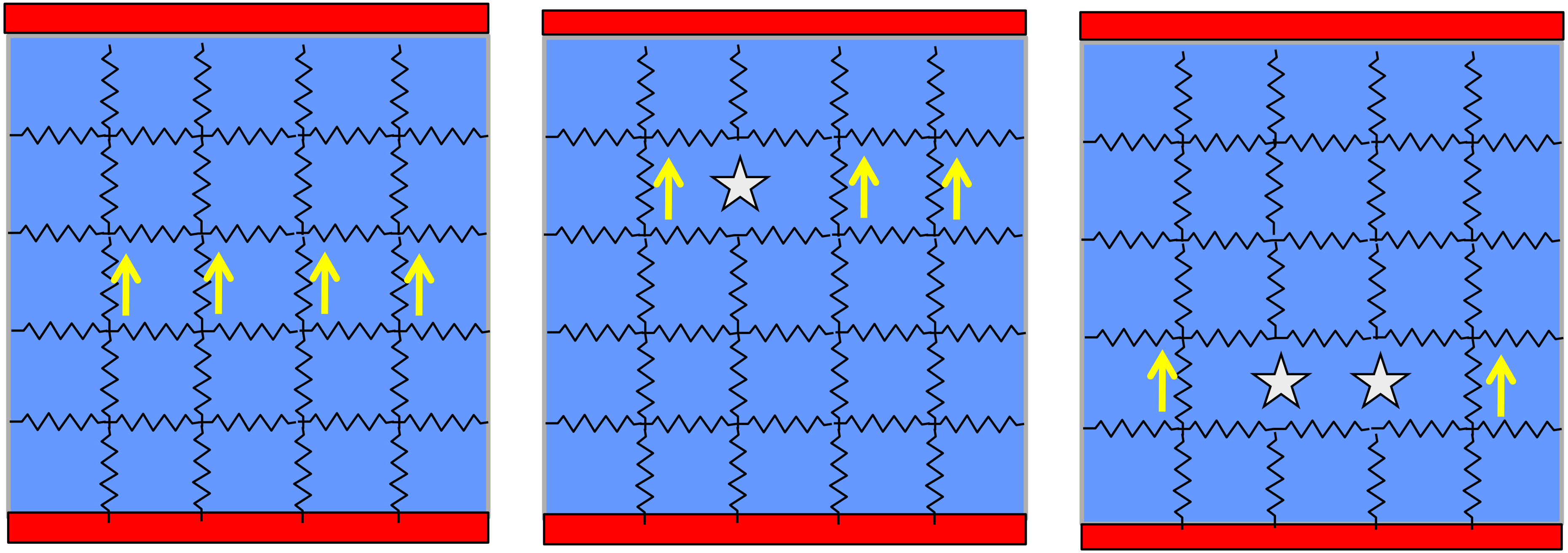


$$E \square E_0 \sqrt{\frac{l_x(p)}{\rho}}$$

$$E = E_0 \left(1 + \frac{l_x}{l_y}\right) = E_0 \left(1 + \sqrt{\frac{l_x}{\rho}}\right)$$

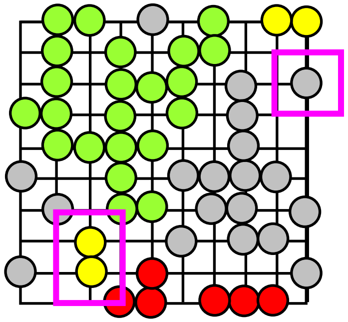
$$\rho \equiv l_y^{\,2} / l_x$$

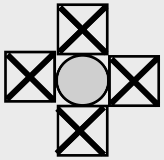
Analogy to resistor network



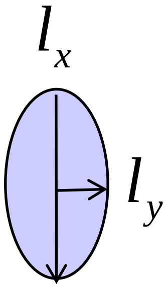
Defects reduce breakdown current ….

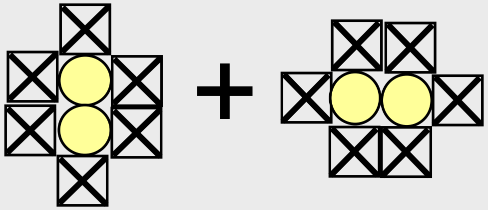
Small-cluster size distribution



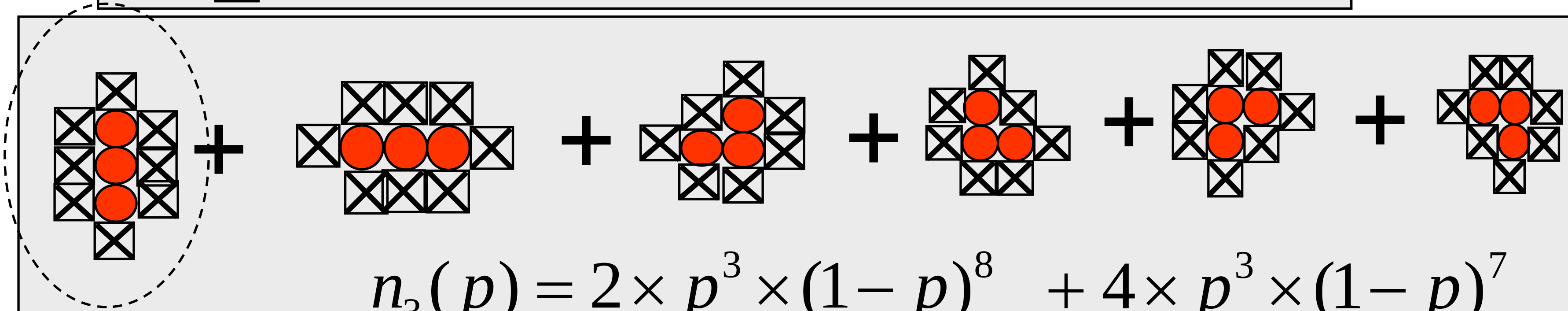


$$n_1(p) = 1 \times p \times (1-p)^4$$





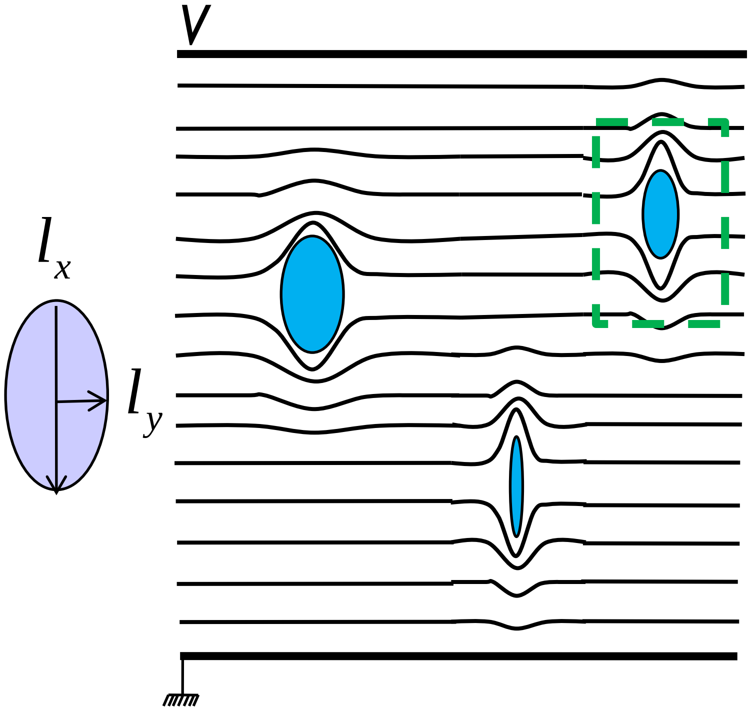
$$n_2(p) = 2 \times p^2 \times (1-p)^6$$

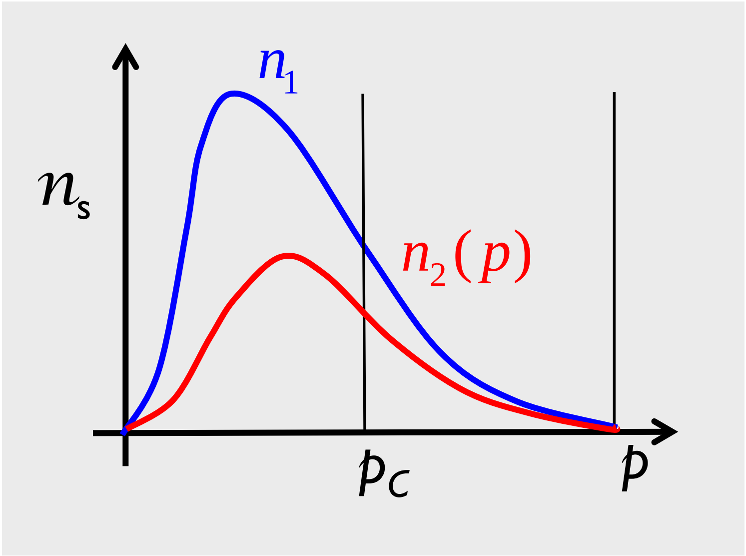


$$n_3(p) = 2 \times p^3 \times (1-p)^8 \quad + 4 \times p^3 \times (1-p)^7$$

$$n_s(p) = \sum_t g_{st} \times p^s \times (1-p)^t$$

Size distribution and critical defect size





$$n_1(p) = L^2 p^{l_x}(1-p)^{2l_x+2}$$

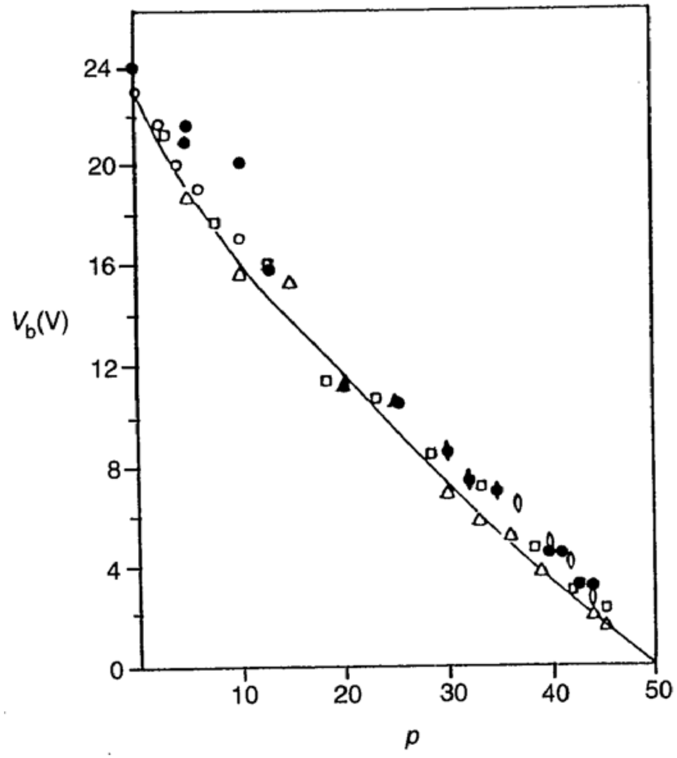
$$\sim L^2 p^{l_x} \ (p \to 0)$$

$$p^{\langle l_x \rangle} L^2 \sim 1 \Rightarrow$$

$$\langle l_x(p) \rangle = \frac{-2\ln L}{\ln p}$$

At a defect level p, most probable size of defect is l_c(p)

Breakdown field for islands of size L_c



$$E_0^{crit}\sqrt{\langle l_x(p)\rangle/\rho}=E_{BD}$$

$$\langle l_x(p)\rangle=\frac{-2\ln L}{\ln p}=\rho\left(\frac{E_{BD}}{E_0}\right)^2=\rho\left(\frac{LE_{BD}}{V_{app}}\right)^2$$

$$\frac{V_{app}}{LE_{BD}}=\sqrt{\frac{\rho\ln p}{-2\ln L}}$$

Smaller p, larger V_{BD}

V_{BD} reduces to zero at sample size L goes to infinity, because large defects is present with probability 1.

V_{BD} distribution close to percolation threshold

$$1-F(\mathrm{E}_0)=\prod_{i=1}^{n}\left[1-f_{\mathrm{i}}(\mathrm{E}_0)\right]$$

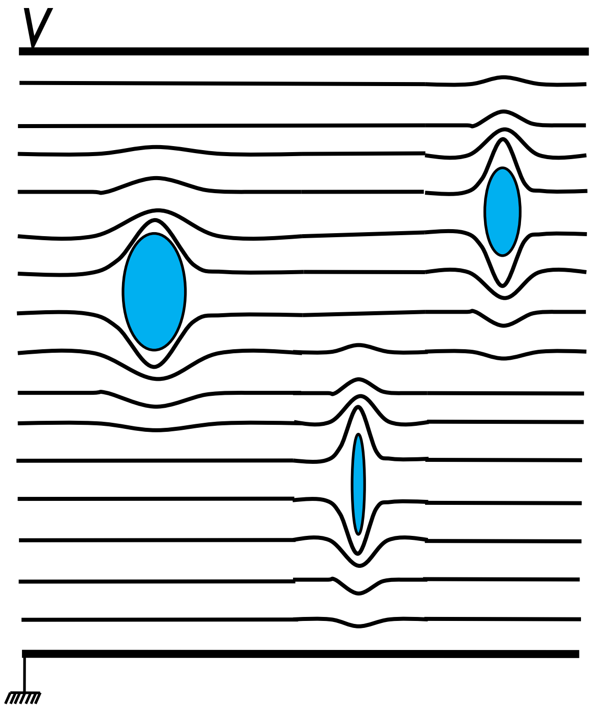
Prob. of failure of i-sized island at E_0

$$\approx 1-\sum_{i=1}^{n} f_{\mathrm{i}}(\mathrm{E}_0)\ \Box\ e^{-\sum_{i=1}^{n} f_{\mathrm{i}}(\mathrm{E}_0)}$$

$$\equiv e^{-A g_1(\mathrm{E}_0)}$$

Area

Defect density that breaks at $\mathrm{E}_0=V_{app}/L$



$$\ln(-\ln(1-F(\mathrm{E}))=\ln A+\ln g_1(\mathrm{E})$$

Size distribution at percolation threshold

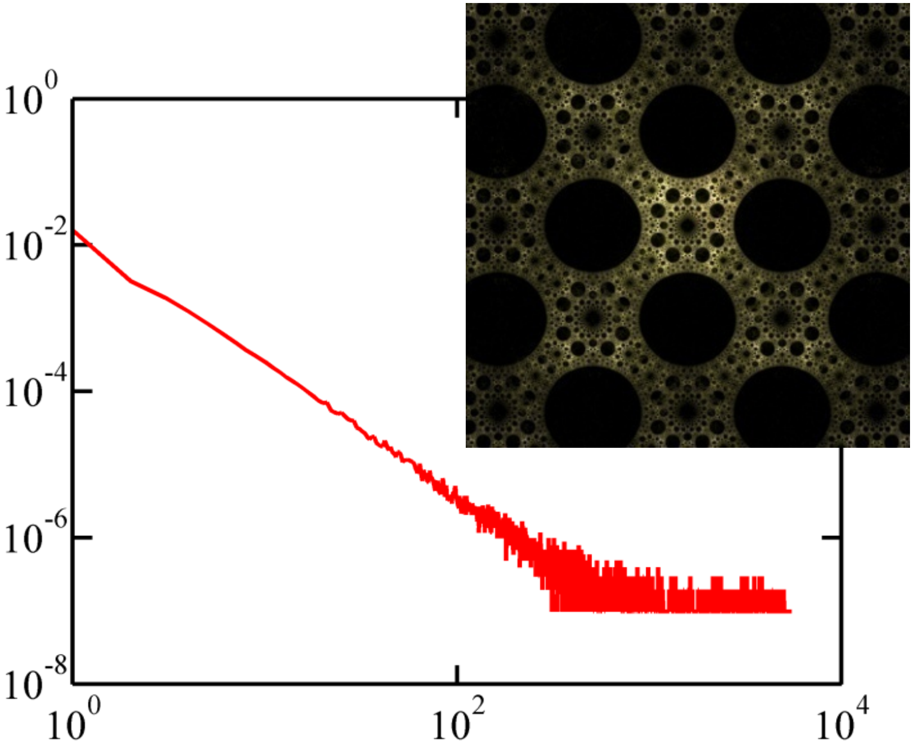
$$g_l(p) \equiv L^{-2} n_l(p)$$

$$= p^{l_x} \times (1-p)^{2l_x+2}$$

$$\sim l_x^{-\tau} @ p = p_c$$

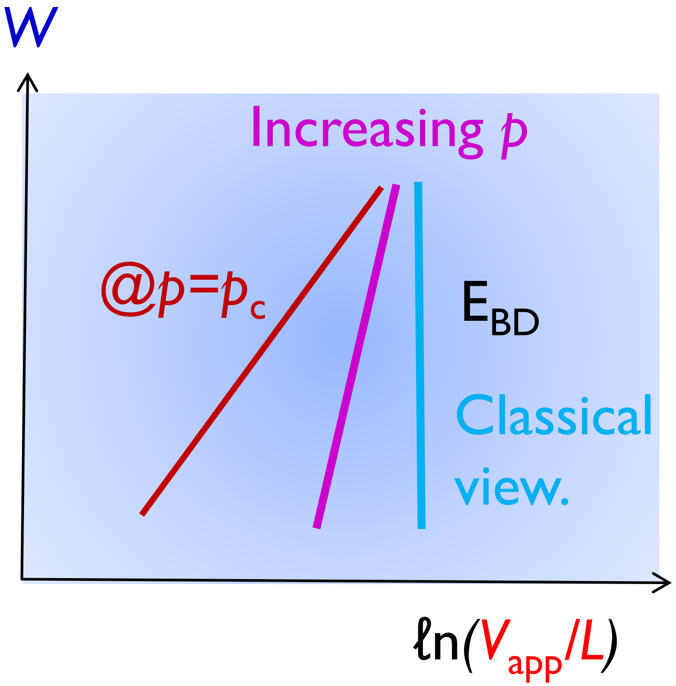
$$\langle l_x \rangle = \rho \left(\frac{\mathrm{E}}{\mathrm{E}_0} \right)^2$$

$$g_l(\mathrm{E}) \sim \rho^{-\tau} \left(\frac{\mathrm{E}}{\mathrm{E}_0} \right)^{-2\tau}$$



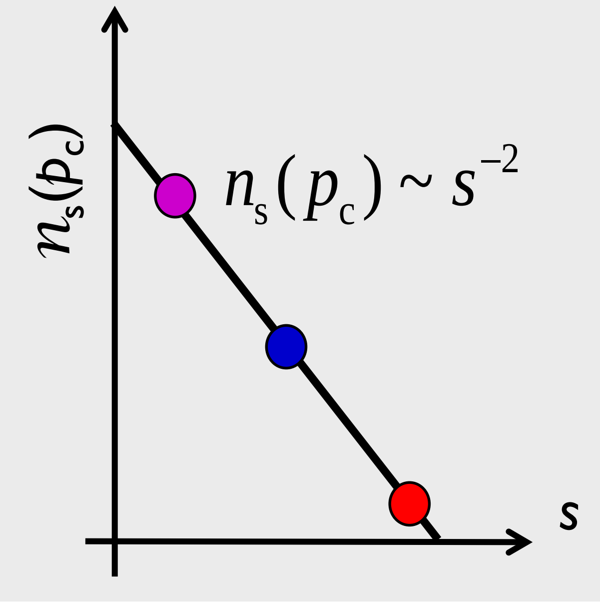
Distributed failure probabilities

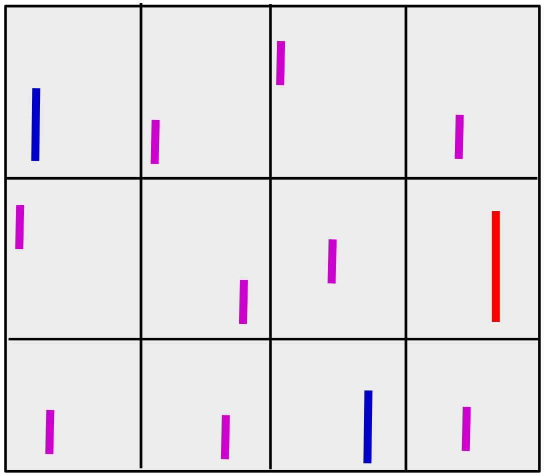
$$
\begin{aligned}
W &\equiv \ln(-\ln(1-F(\mathrm{E}))) \\
&= \ln A + \ln g_1(\mathrm{E}) \\
&= \ln\left(A\rho^{-\tau}\right) + 2\tau \ln\left(\mathrm{E}_0/\mathrm{E}_{\mathrm{BD}}\right) \\
&= \ln(A\rho^{-\tau}) + 2\tau \ln\left(\frac{1}{\mathrm{E}_{\mathrm{BD}}}\frac{V_{\mathrm{app}}}{L}\right)
\end{aligned}
$$

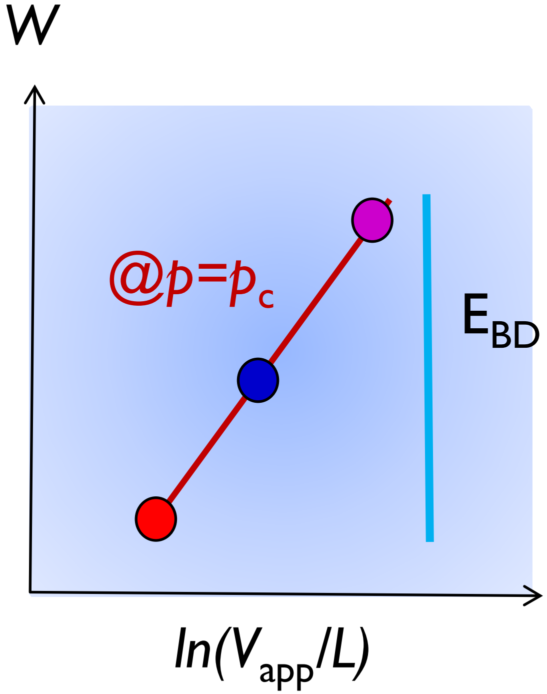


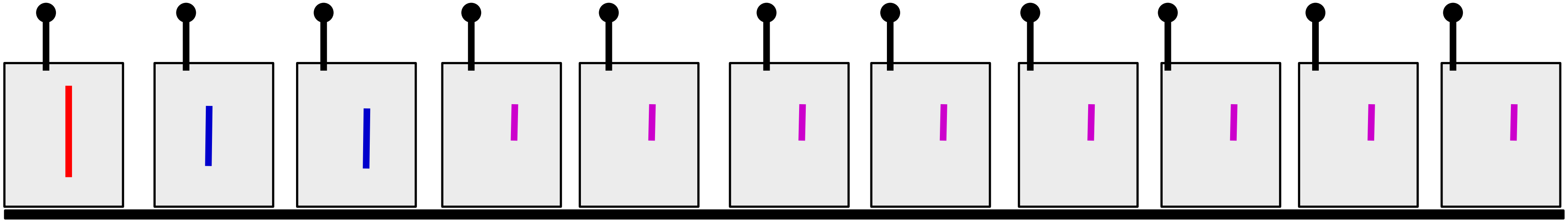
HW: Show that larger area oxides fail at smaller voltages.

What does it all mean (ramp voltage tests) ?









Conclusions

The basic steps of breakdown processes are essentially the same for thin and thick oxides; the key differences are

1) Breakdown in thick oxides in extrinsic, dominated by defects, while that of thin oxide is intrinsic, dominated by contacts.

2) Breakdown in thick oxides is correlated (Lichtenberg figures), while the BD in thin films is uncorrelated.

3) The breakdown strength of thick oxides is often dramatically reduced due to pre-existing defects. In this sense, the physics of fracture and the physics of dielectric breakdown are closely related.

References

- 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.
- Plasma charging figure taken from http://www.timedomaincvd.com/CVD_Fundamentals/plasmas/plasma_damage.html

Review questions

1. What is the difference between extrinsic vs. intrinsic breakdown?
2. Does gas dielectric have extrinsic breakdown? Why or why not?
3. What does ESD damage and the plasma damage to thin oxides?
4. Can you explain the physical meaning of infant mortality ? How does it relate to yield of semiconductor manufacturing?
5. Can you reinterpret the Apgar tests in terms of infant mortality?
6. What is the difference between the Weibull for thick vs. thin oxides?