Network for Computational Nanotechnology (NCN)
presents

The Long and Short of Pick-Up Stick Transistors: A Promising Technology For Micro- and Macro-electronics

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MIT, Univ. of Florida, Univ.of Illinois, Morgan State, Northwestern, Purdue, Stanford, UTEP

Collaboration/Support

Theory:

- Prof. J. Murthy (ME),
- N. Pimparkar (EE) & S. Kumar (ME)

Experiments

- J. Rogers (UIUC),
- E. Snow (NRL), G. Blanchet (Dupont), P. Leon (Nanosys)

Support

- NCN, Agilent Technologies, Nanosys Inc.
- R. Ruess (DAPRA)

Presentation Outline

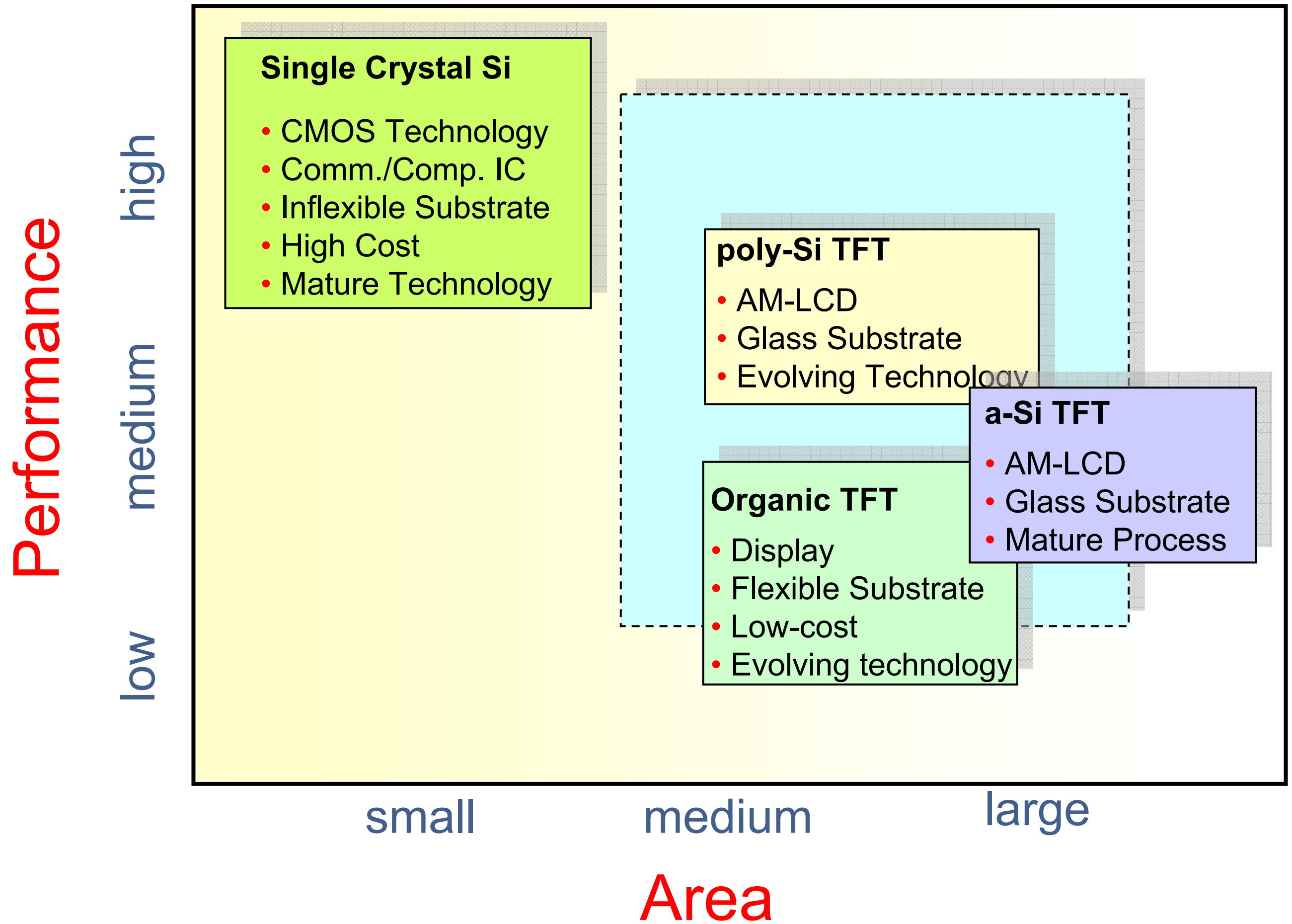
- Background/Motivation
- Theory of Stick-Composites
- Applications:
  - *Microelectronics*
  - *Macroelectronics,*
  - *Organics …*
- Conclusions

The “Other” Transistor

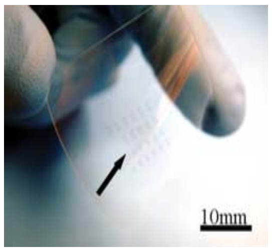
Displays

Microprocessors

Landscape of Electronics



Transparent



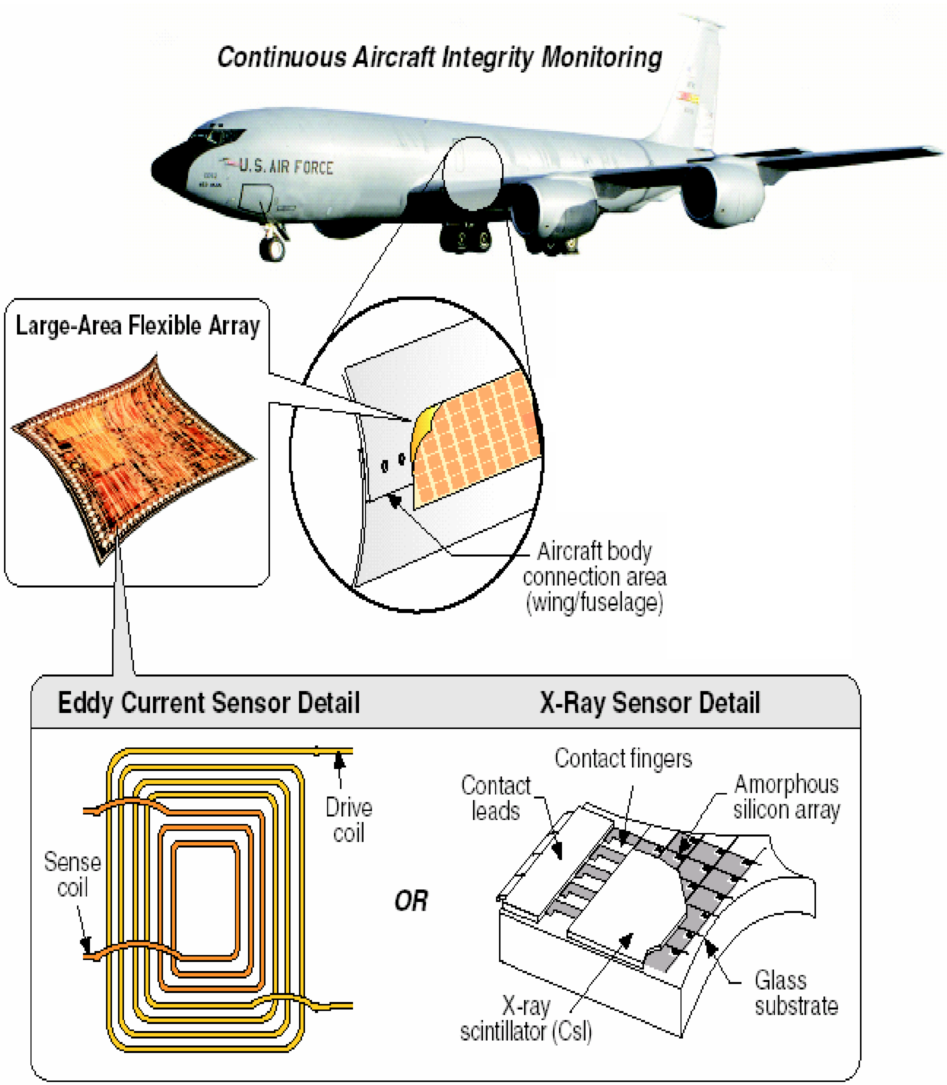
…. & Flexible

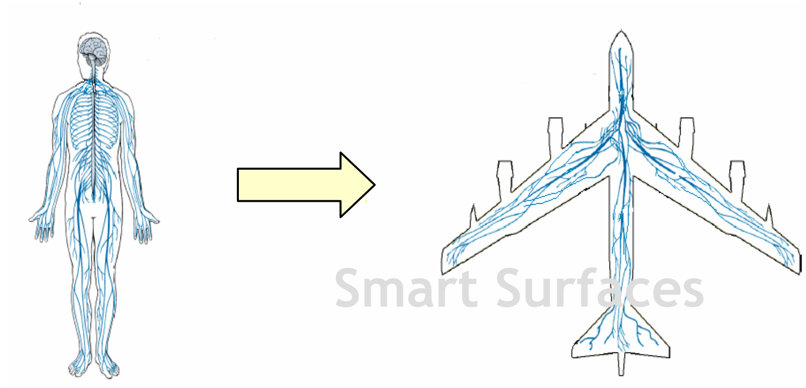
Plastic Logic's e-paper

Seiko wristwatch

Philips Readius Reader

Smart Surfaces

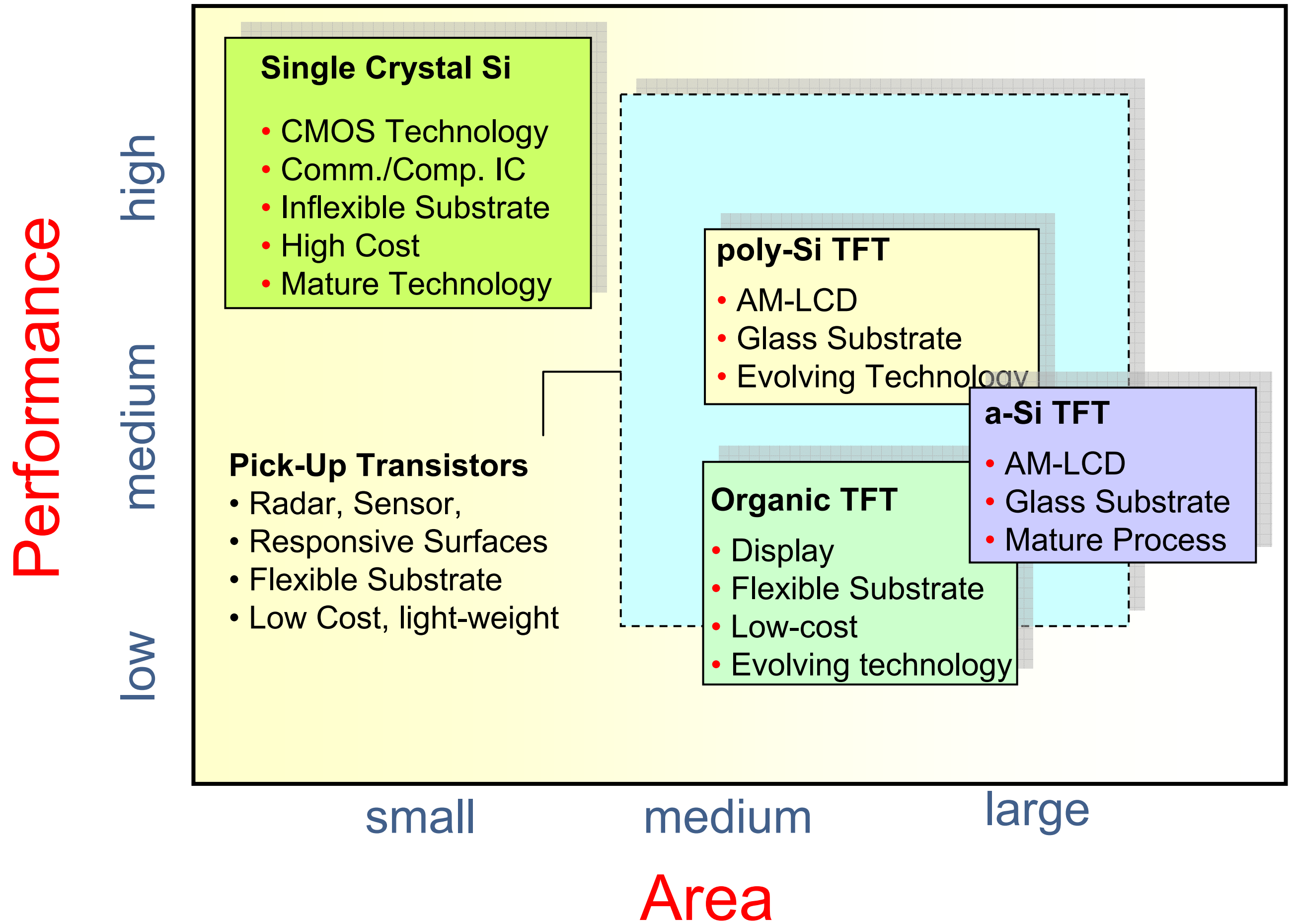




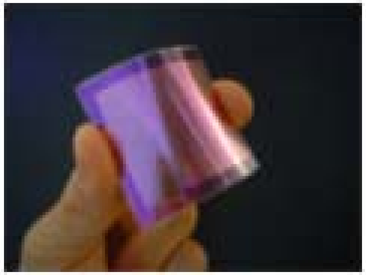
- *Local Sensing & Real-time corrective action*
- *Sensing & Information distribution and global reaction*

Bob Reuss, DARPA

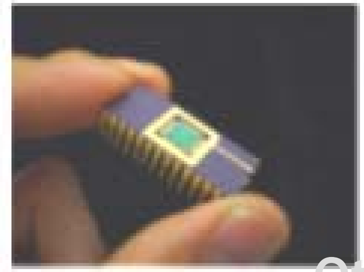
A New TFT Technology



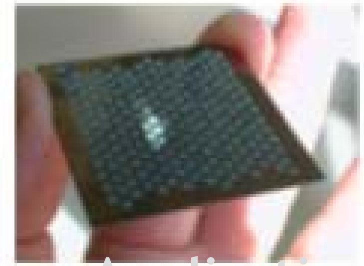
… Other Applications

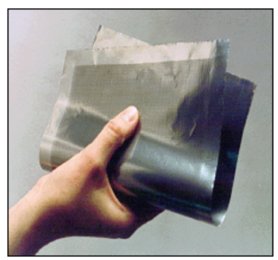

Conformal Solar Cells

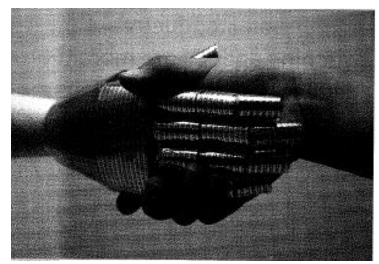

Flexible Electronics


Memory

… Other Applications


Drug Discovery Substrates


Steel


Artificial Skin

Nanosys
Univ. of Tokyo

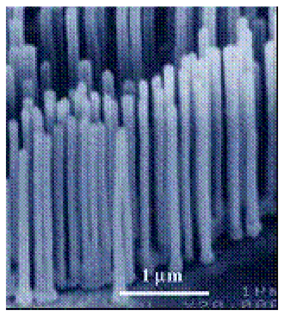
- Many exciting experimental reports over past several years
- Capability of theory/simulation is essentially nonexistent

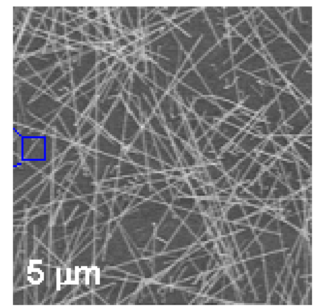
Composites of Si-NW & CNT

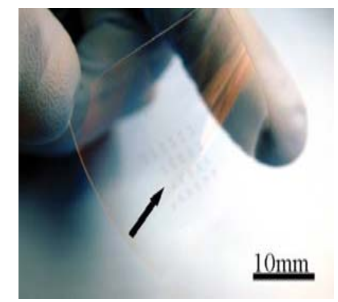
Grow on high temp. substrate

Disperse in solvent Spread on soft substrate

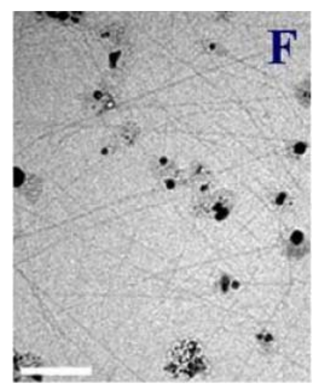
Si-NW



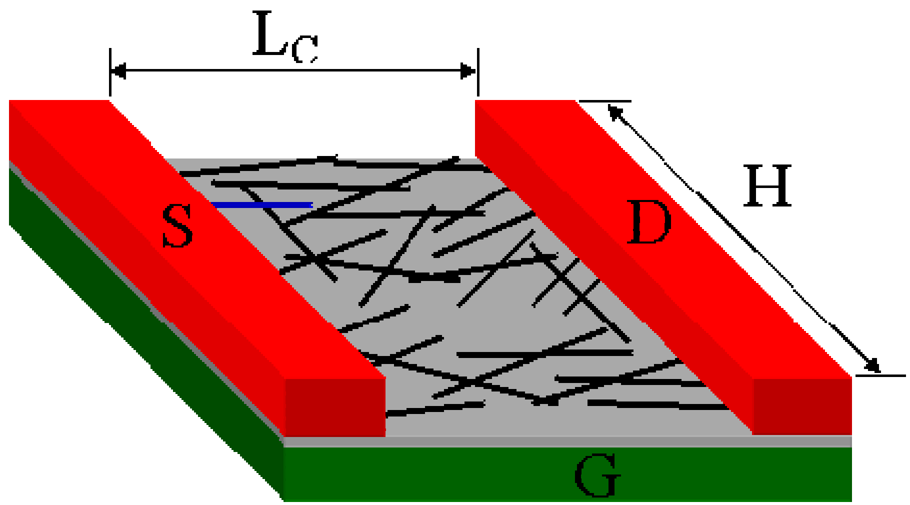




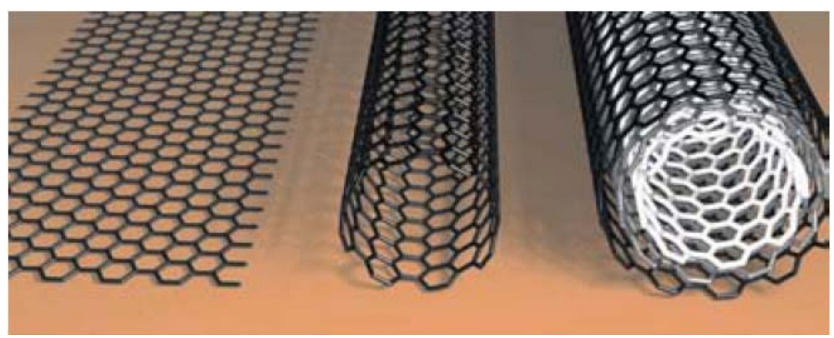
CNT



Nanosys Inc.
Igal Schatz, Polymer Physics Review, 2005



Individual Sticks

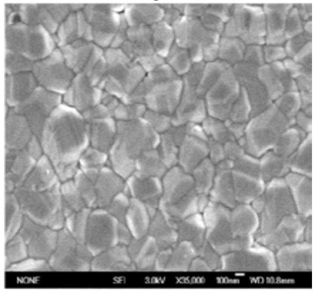


Well developed theory of transport in crystals

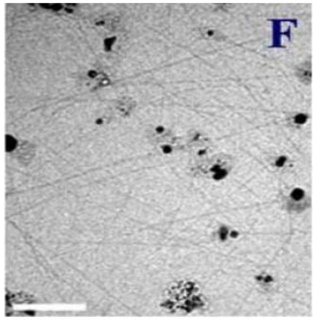
Therefore, people often …..

- ❑ Locally homogenize the random media to make it look like periodic solid, and
- ❑ use the theory of crystals for approximate properties of random media ….

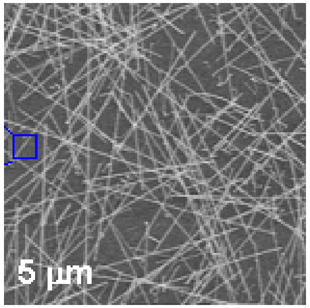
poly-Si



CNT

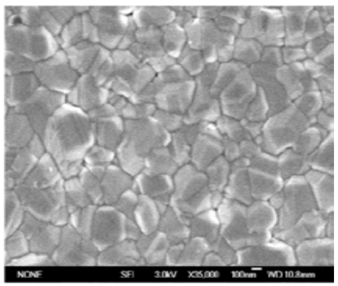


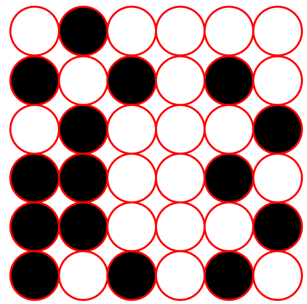
Si-NW

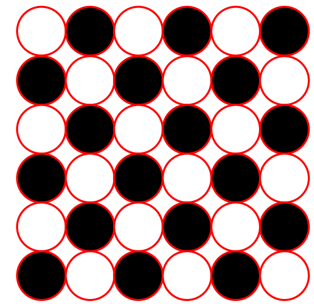


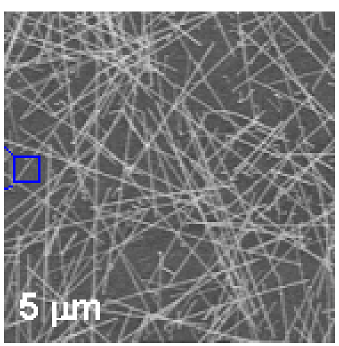
Effective Media Approach

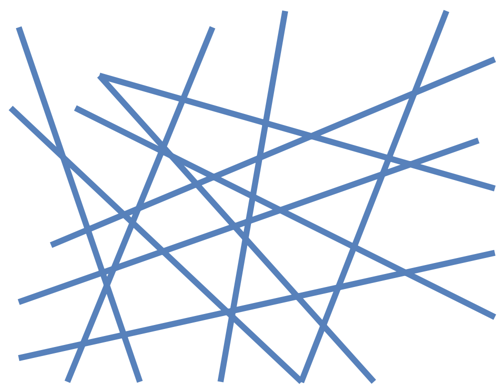
System	Random	Periodic

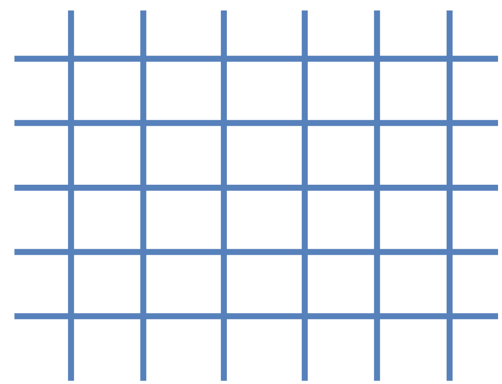






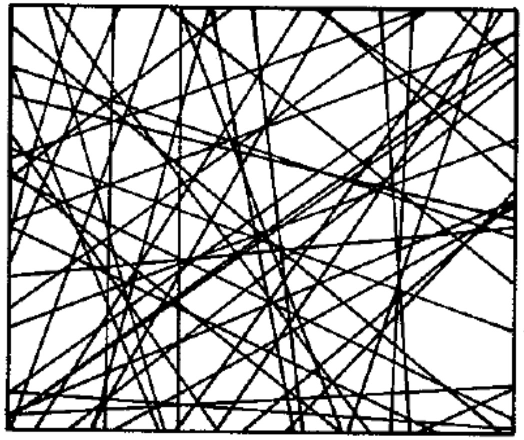




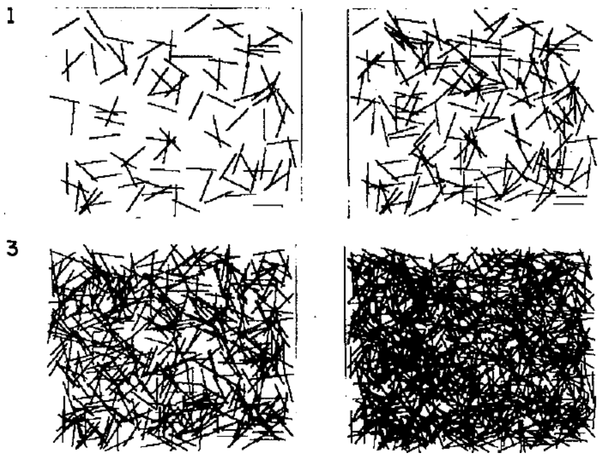


Reasonable for amorphous media, but not really good for nanocomposites …

Stochastic Geometry of Random Sticks

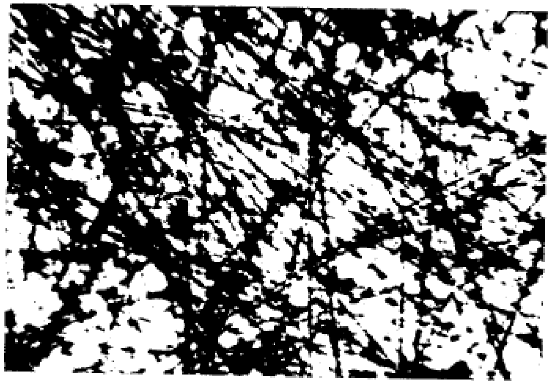


Poisson Line Process



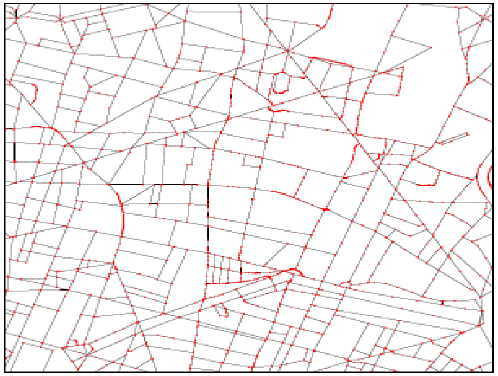
Paper

(B. Key, Random Walk in Fractal Dimension)



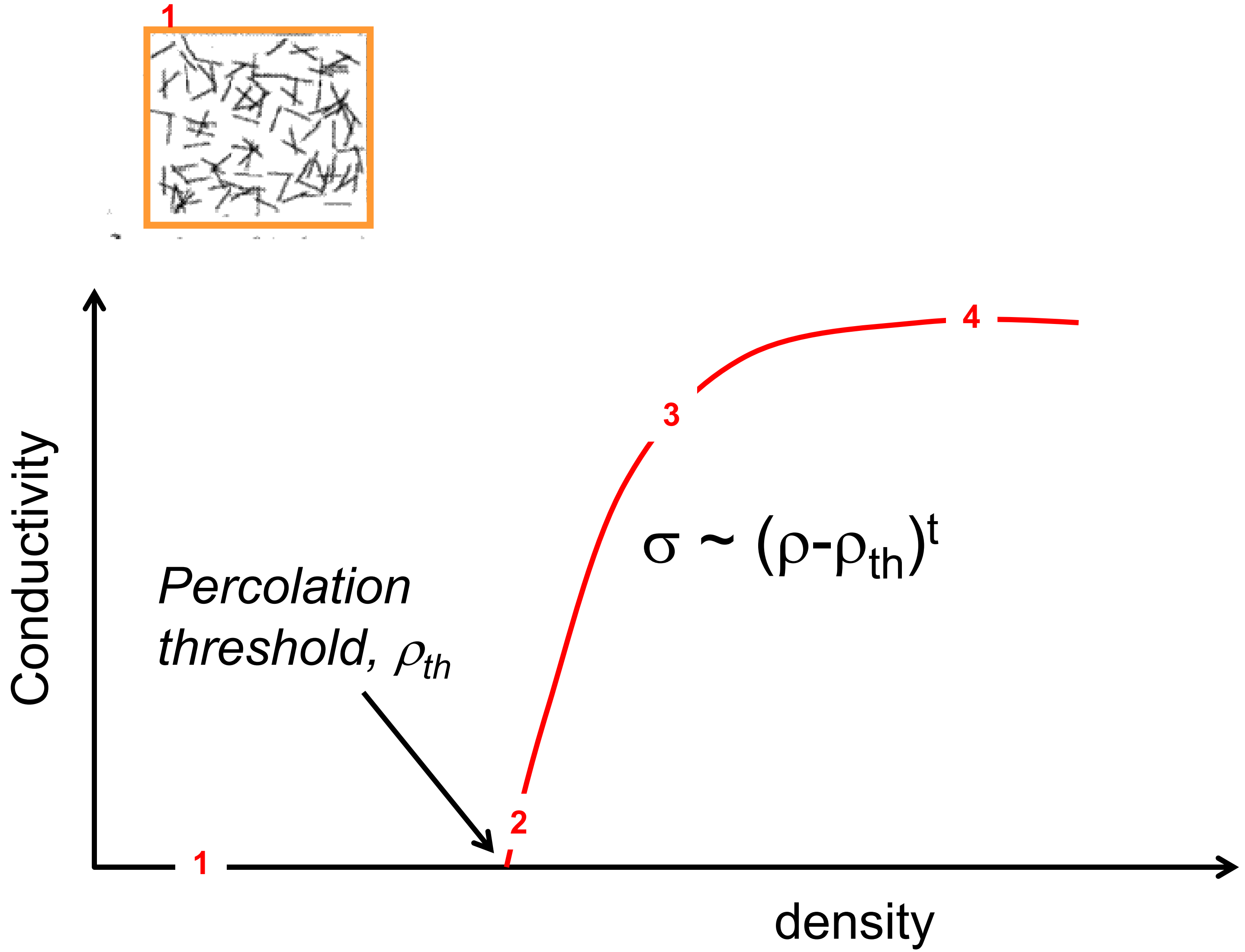
Fibrous Aerosol Filter

(Fuchs, Faraday Div. of Chem. Soc. Proc. 7, 1973.)

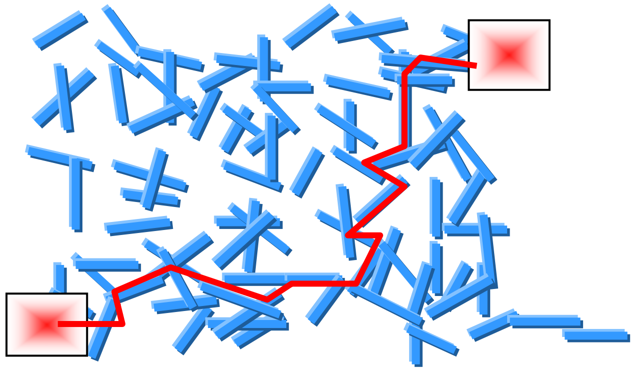


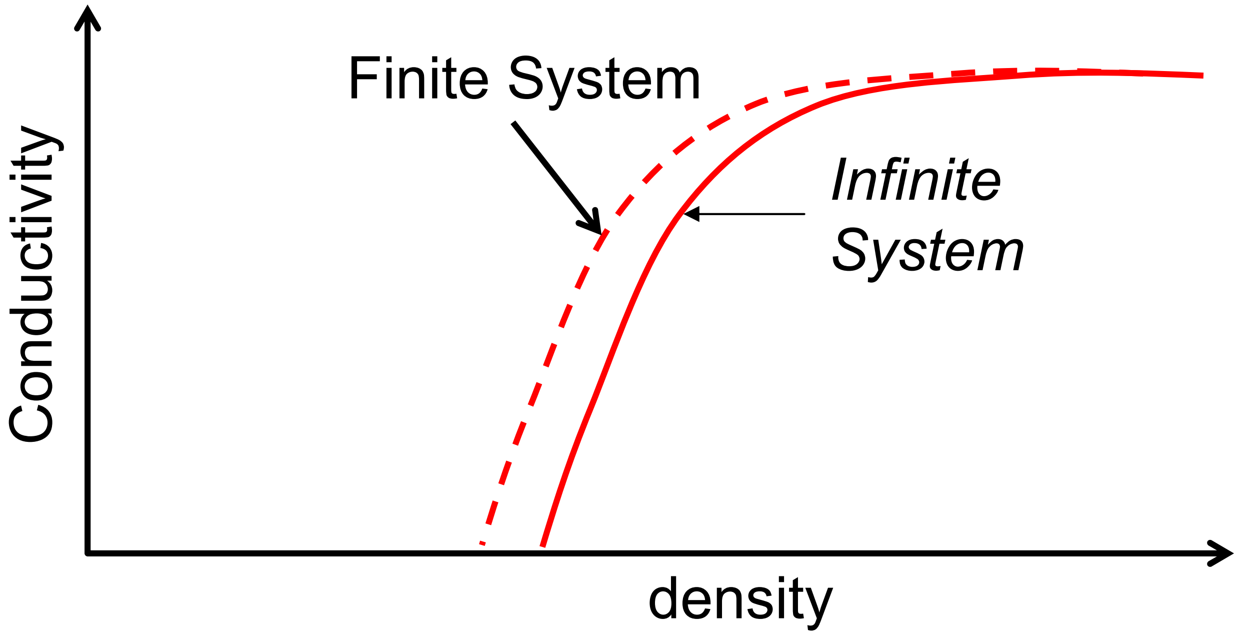
Telecom grid in Paris

Percolation in Random Media



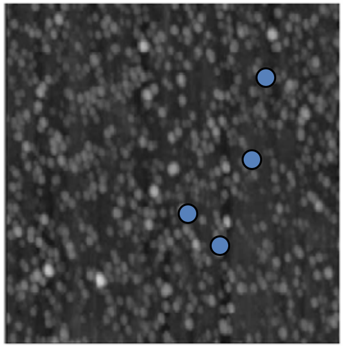
Soft Threshold for Finite Size Percolation



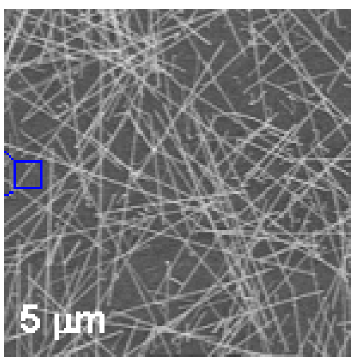


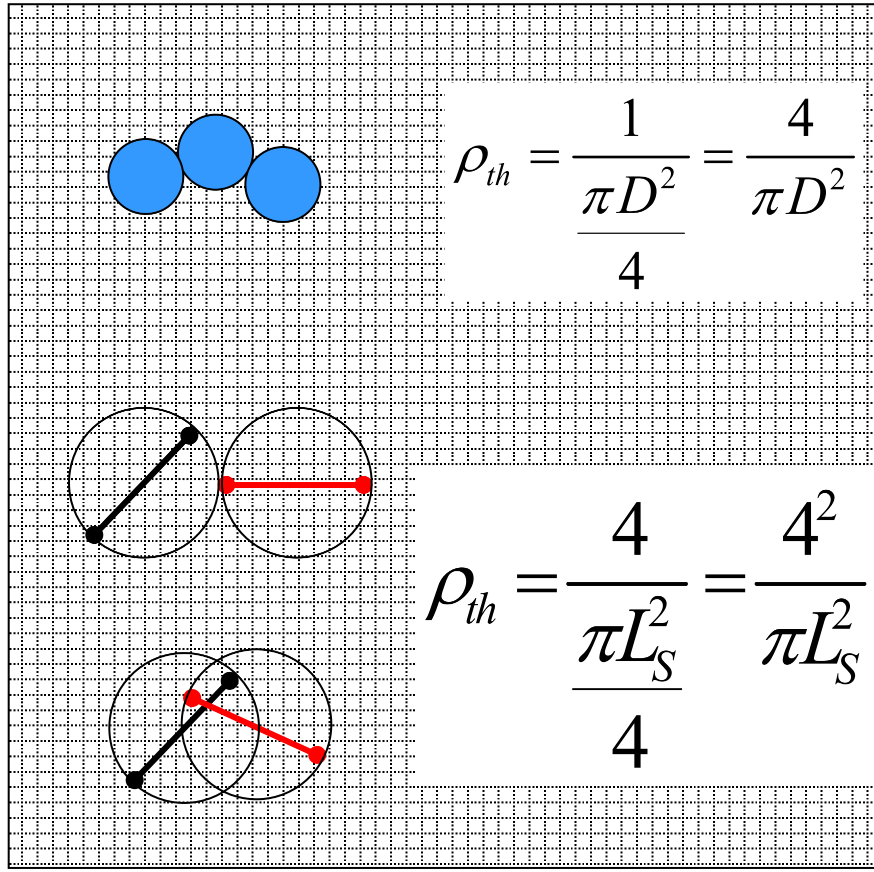
Percolation Threshold for Stick Transistors

Disk percolation



Stick percolation





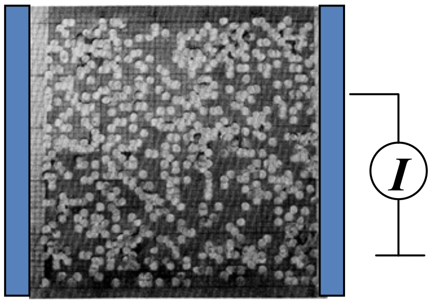
$$\rho_{th} = \frac{1}{\frac{\pi D^2}{4}} = \frac{4}{\pi D^2}$$

$$\rho_{th} = \frac{4}{\frac{\pi L_S^2}{4}} = \frac{4^2}{\pi L_S^2}$$

Exact Result $$\rho_{th} = \frac{4.26^2}{\pi L_S^2}$$

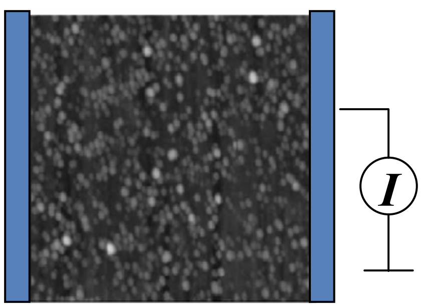
Electrical Percolation

3 mm holes in Conducting Paper



Dubson, PRL, 27, 1719, 1971.

60-nm bismuth clusters



Schmelzer, PRL, 88 (22), 226802, 2002

- Geometry of random sticks well understood.
- Understanding of electrical conduction work in random stick network has been restricted to

  Infinite systems
  Linear response
  Homogenous sticks

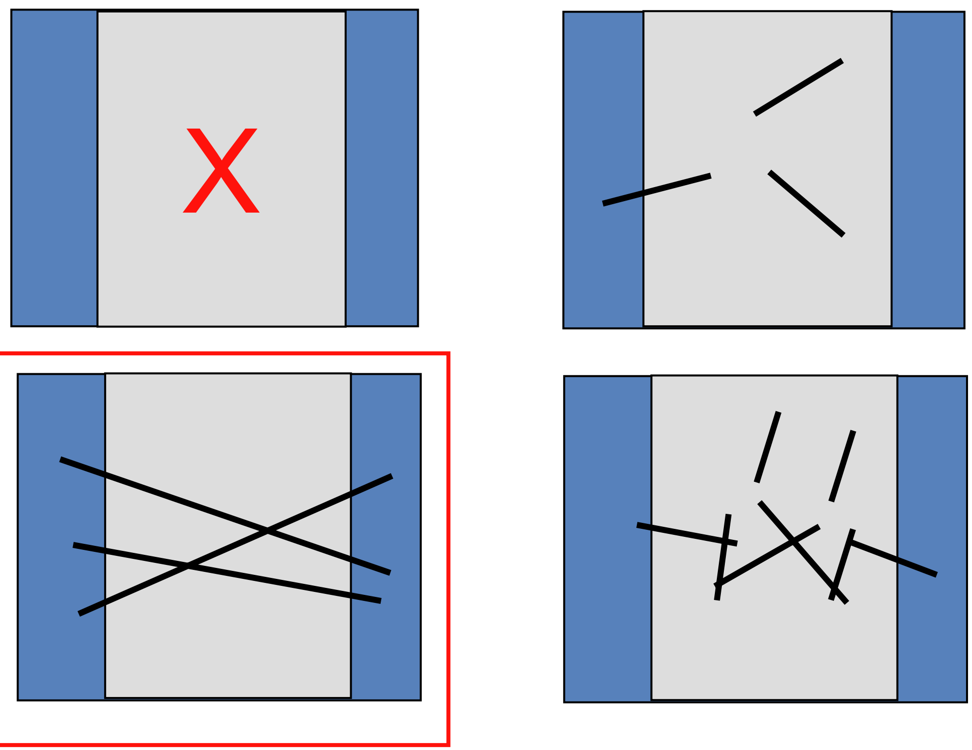
- Classical literature has few comparison with experiment

Four Phases of Stick Percolation

$L_S > L_C$ | $L_S < L_C$

$\rho < \rho_{th}$

$\rho > \rho_{th}$



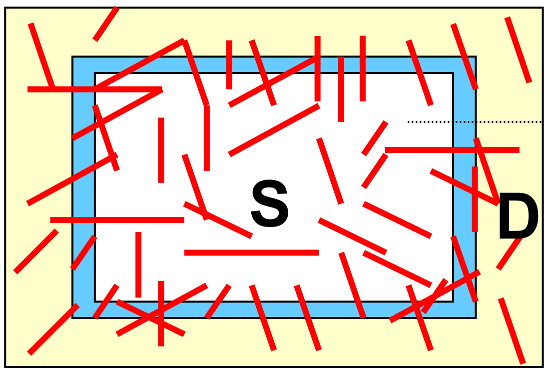
- Organics
- Numerical
- *S. Kumar*
  Prof. Murthy

- Macroelectronics
- Numerical
- *S. Kumar &*
  N. Pimparkar
  Prof. Murthy

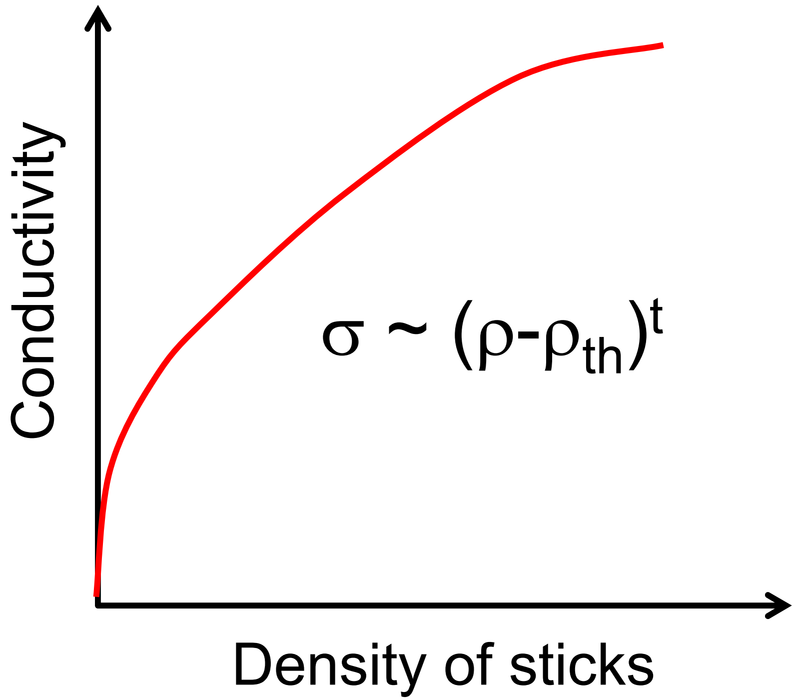
- Microelectronics
- Analytical Models
- *N. Pimparkar*

Prof. Rogers (UIUC),
Dr. Snow (NRL)
Prof. Hines (Maryland)

Transport in Short Devices, $L_S > L_C$



Seidel et al., Nano Letters, 831, 2004

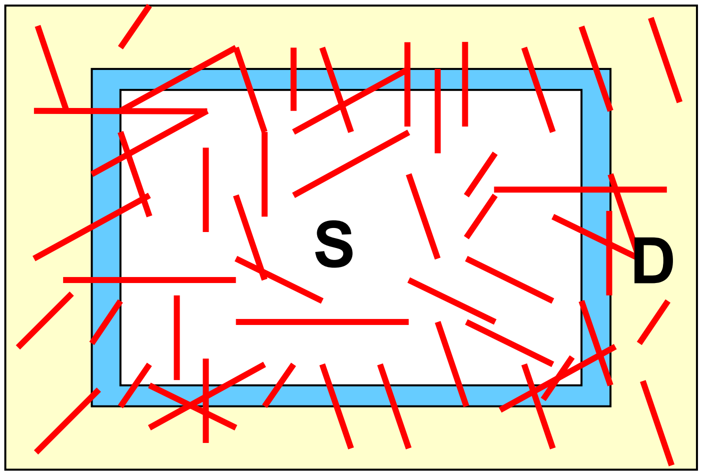


No threshold for percolation …

Calculating Current

Low drive current, Site-specific Placement

Analysis by Fan Diagram!



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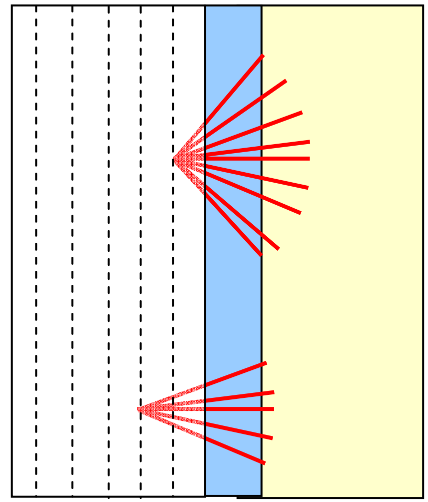
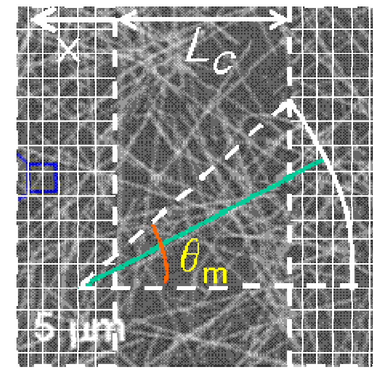




$$N_S = \sum_x \frac{\theta_m(x)}{\pi/2}$$

$$= \frac{\pi D_x L_S}{2}\left\{\sqrt{1-R_S^{\,2}} - R_S \cos^{-1} R_S\right\}$$

$$R_S = L_S / L_C$$

- *Generalized Buffon Needle Problem!*

Analytical Model

- Ballistic Limit

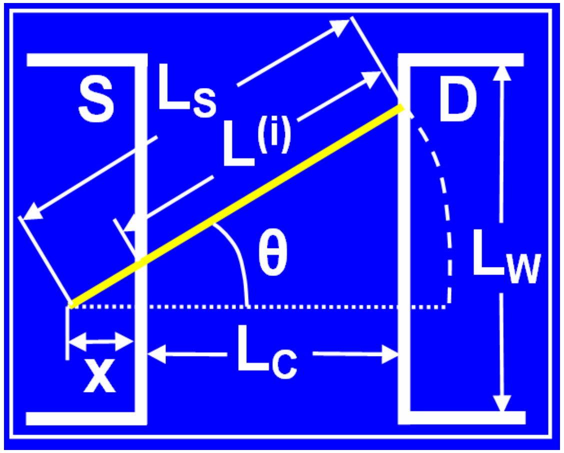
$$\frac{I_B}{f_1(V_D,V_G)} = \sum_1^N 1 = \int_0^{\theta_{\max}} 2D_C/\pi(L_S\cos\theta - L_C)d\theta$$

- Diffusive Limit

$$\frac{I_D}{f(V_D,V_G)} = \sum_1^N \frac{1}{L^{(i)}}$$

- Velocity Saturation

$$\frac{I_{sat}}{f(V_D,V_G)} = \sum_1^N 1$$



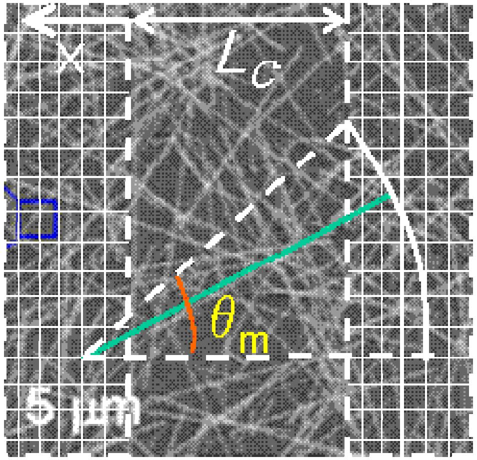
- Intermediate L_C

$$\frac{I_T}{f(V_D,V_G)} = \sum_1^N \frac{\lambda}{\lambda + L^{(i)}} = \int_0^{\theta_{\max}} \frac{2D_C}{\pi} \frac{\lambda}{\lambda + L_C/\cos\theta}(L_S\cos\theta - L_C)d\theta$$

I-V Characteristics for LS > LC

$$I_D = I_D(V_G, V_D, L_C, T_{ox}, N_S, L_S, D_x)$$
$$= g(D_x, N_S, L_S, L_C) \times \zeta(V_G, V_D, L_C, T_{ox})$$

Geometry × electrical



- ***Short channel limit with ballistic Transport***

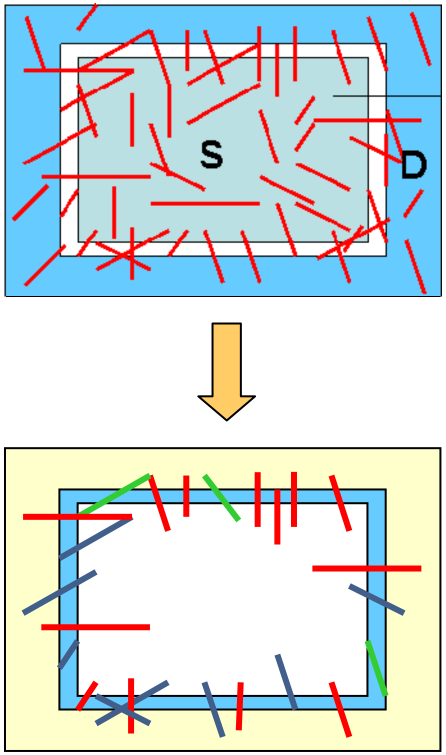
$$g = (2/\pi) D_x L_s \left(\sqrt{1 - R_S^2} - R_S \cos^{-1} R_S \right)$$
$$\zeta = L_W C_{ox} [V_G - V_{TH}] v_T$$

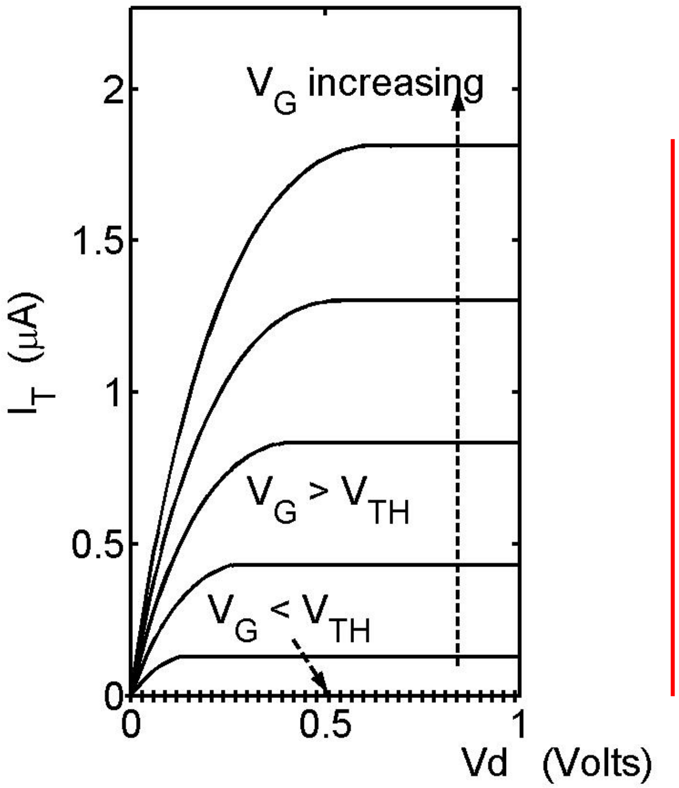
- ***Long Channel Limit with Saturation***

$$g = \frac{2D_C}{\pi b^2} \left[b g_N(R_S) - \cos^{-1} R_S + \frac{2(bR_S + 1)}{\sqrt{b^2 - 1}} \tanh^{-1} \frac{(b-1)\tan(\theta_S/2)}{\sqrt{b^2 - 1}} \right]$$
$$\zeta = L_W C_{ox} \mu_0 [(V_G - V_{TH}) V_D - V_D^2 / 2]$$

Scattering Limited Transport

$$g = \frac{2D_C}{\pi b^2}\left[b g_N(R_S) - \cos^{-1} R_S + \frac{2(bR_S+1)}{\sqrt{b^2-1}} \tanh^{-1} \frac{(b-1)\tan(\theta_S/2)}{\sqrt{b^2-1}} \right] \qquad \zeta = L_W C_{ox} \mu_0 [(V_G - V_{TH})V_D - V_D^2/2]$$

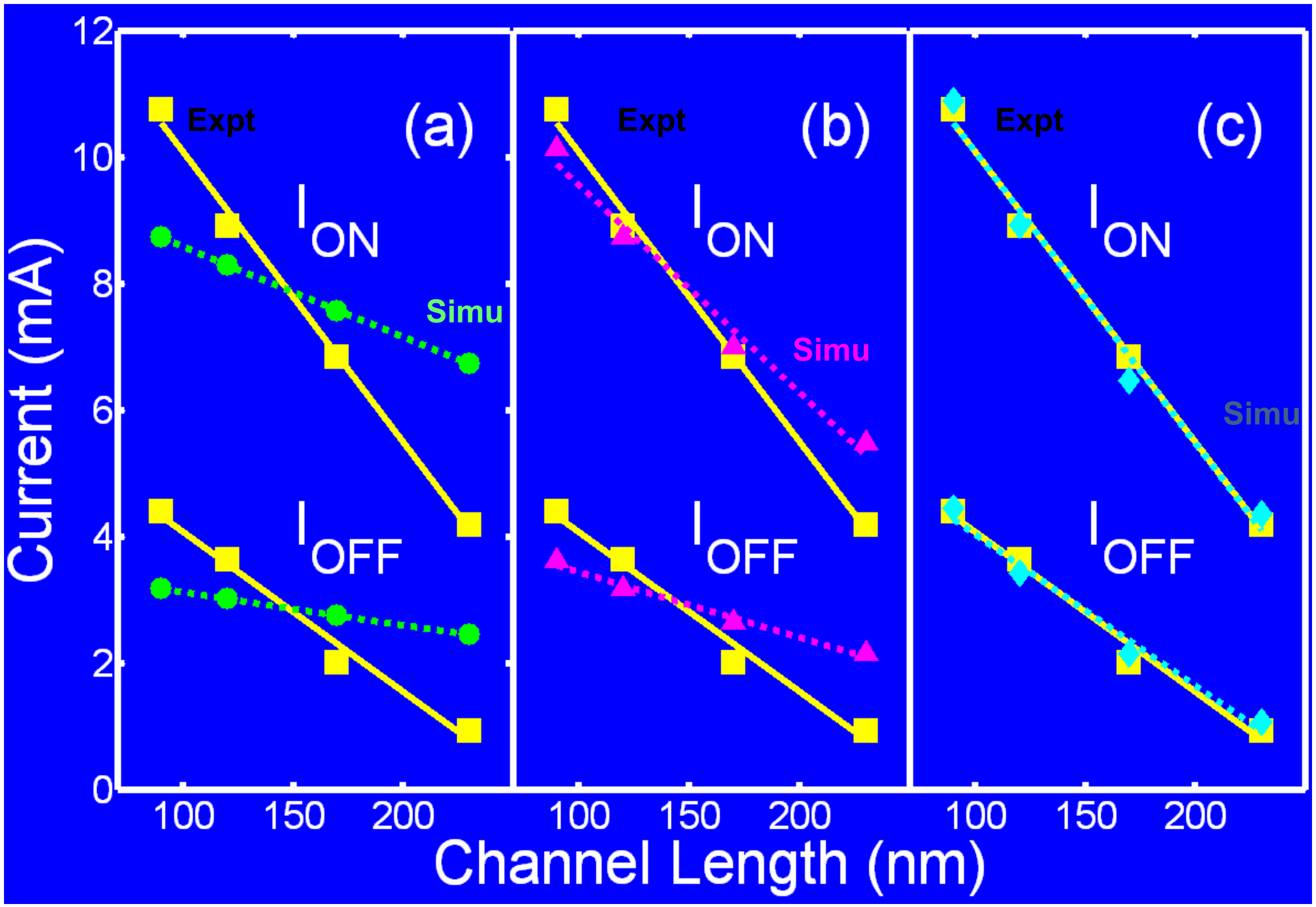




Although the I-V looks classical, it is not just a sum of individual I-V s!

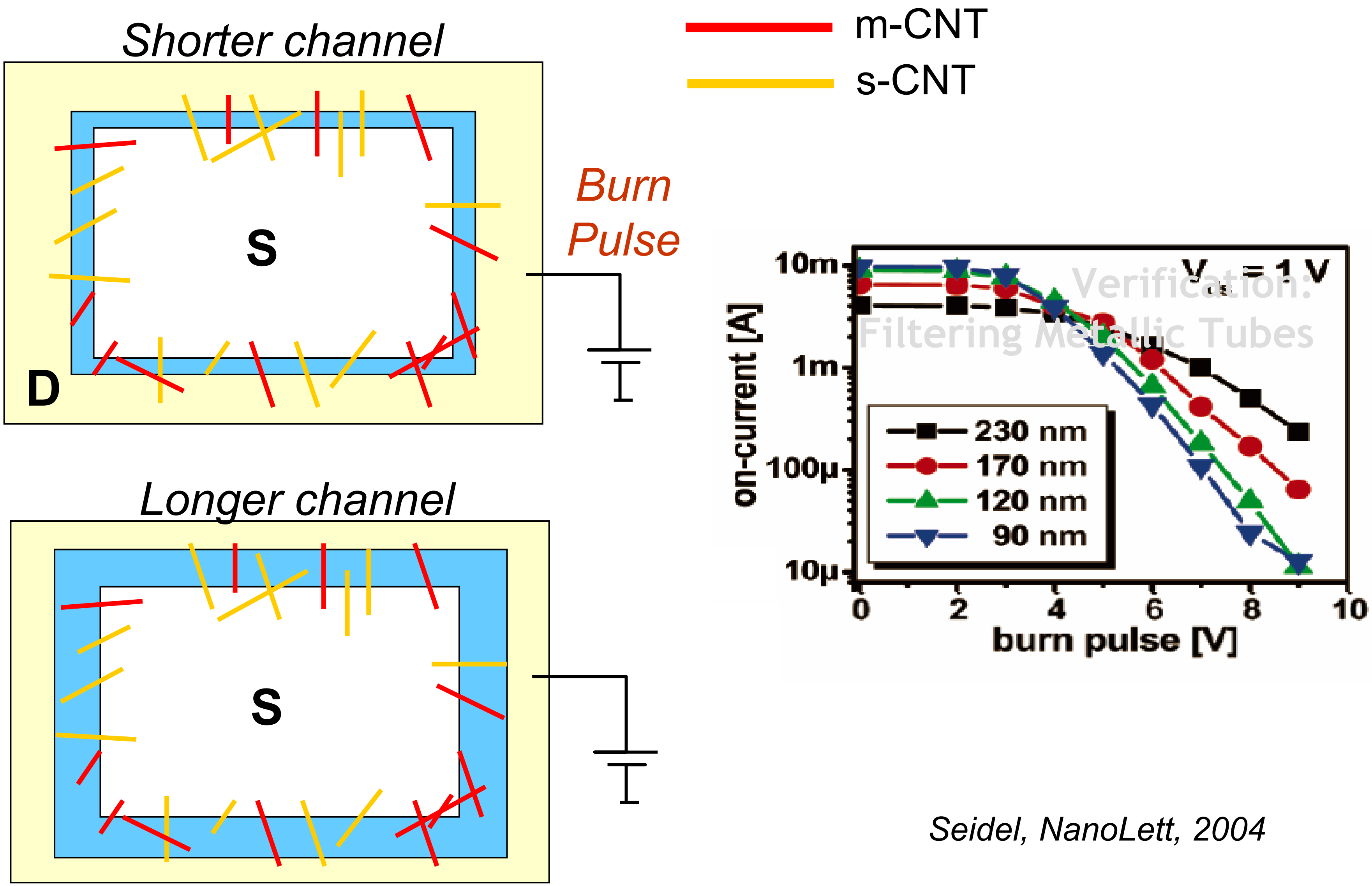
On and Off Current Scaling

Statistics + Scattering + Length pdf



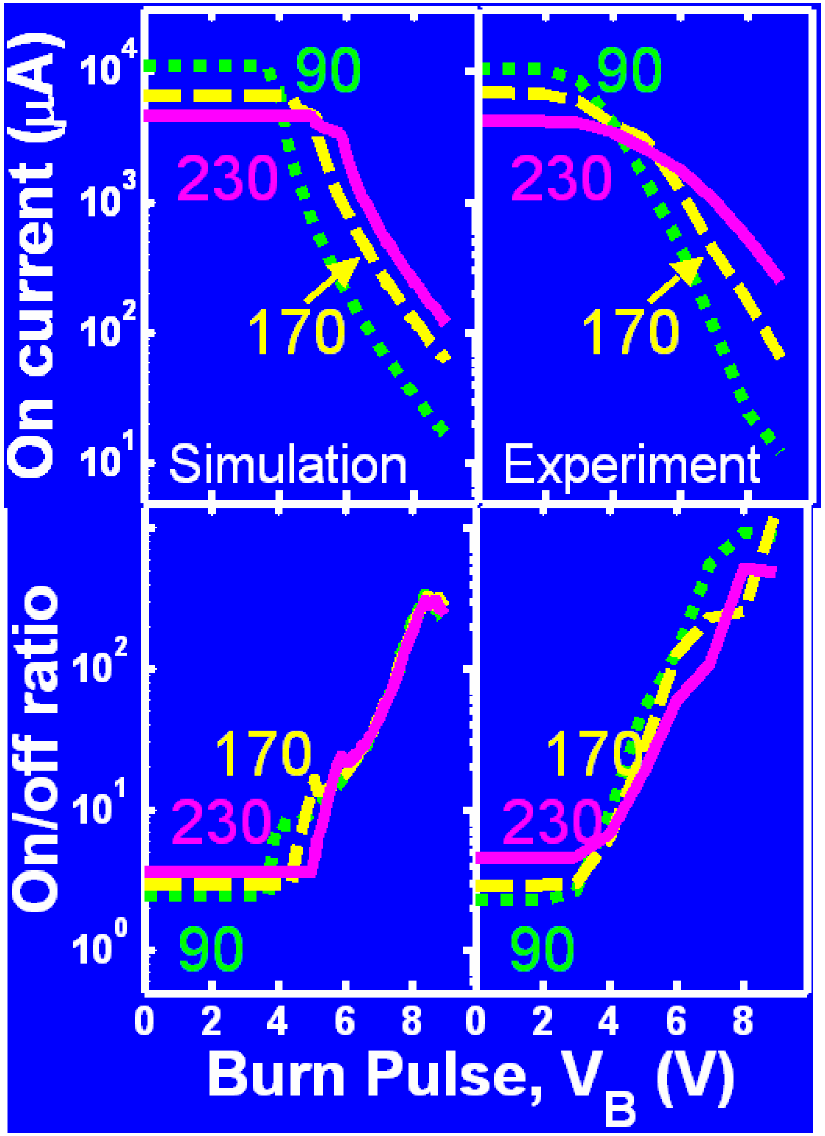
Nano Lett. 2004 p.831
Pimparkar, *IEDM* 2005

Verification: Filtering Metallic Tubes

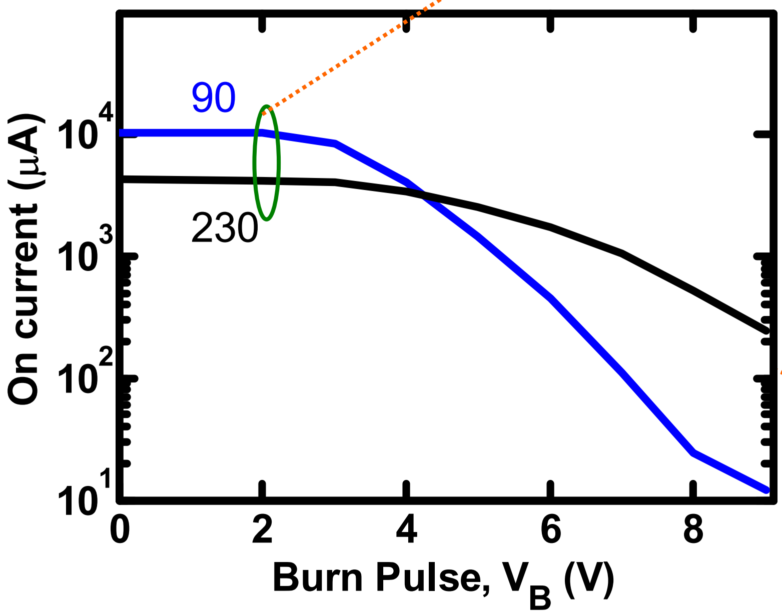


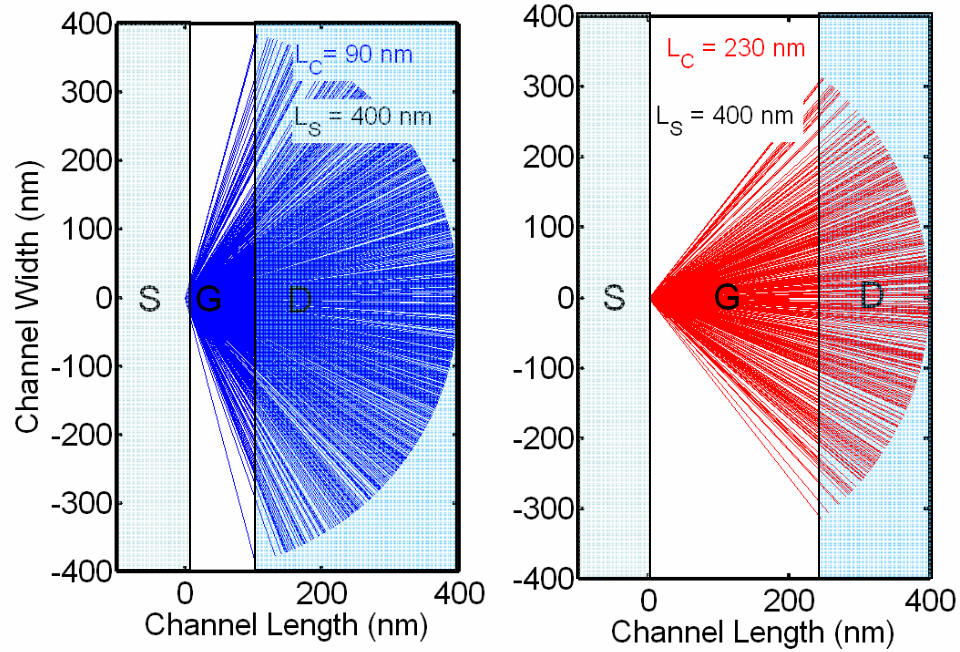
Seidel, NanoLett, 2004

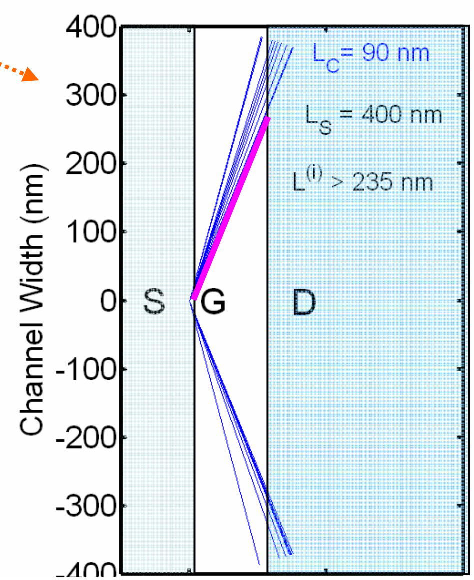
Experiment Matches Simulation !



Interpretation ..







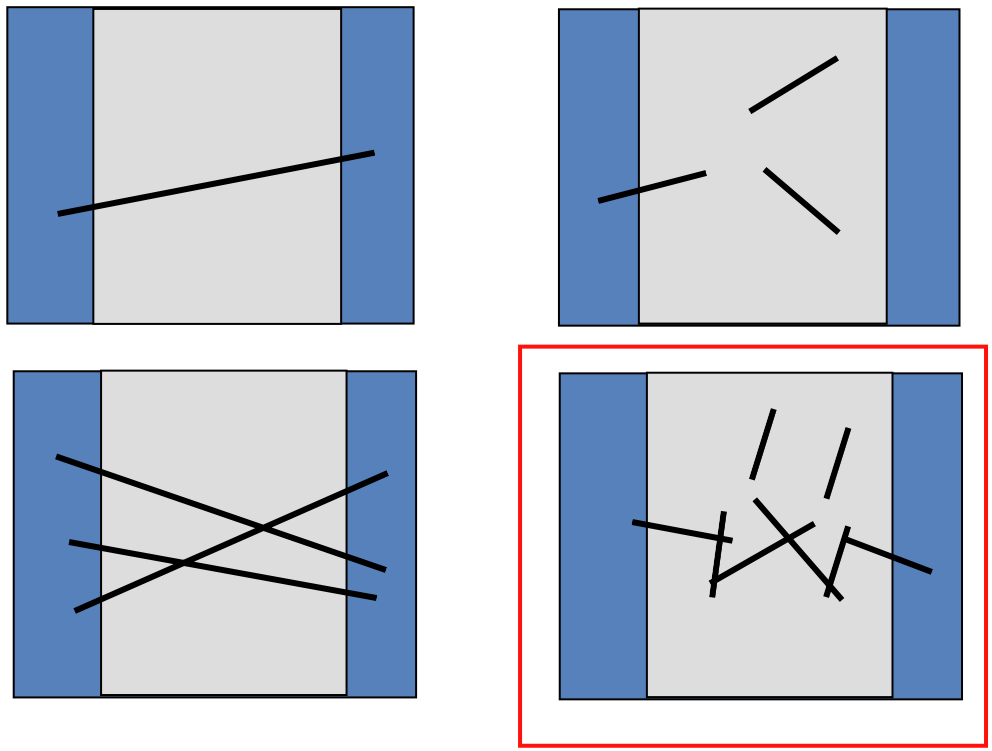
$$L_B = \frac{V_B}{I_{CRIT}}$$

Four Phases of Stick Percolation

$L_S > L_C$ $\quad$ $L_S < L_C$

$\rho < \rho_{th}$

$\rho > \rho_{th}$



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- *S. Kumar*

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- Numerical
- *S. Kumar & N. Pimparkar*

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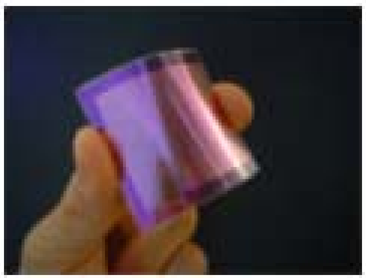
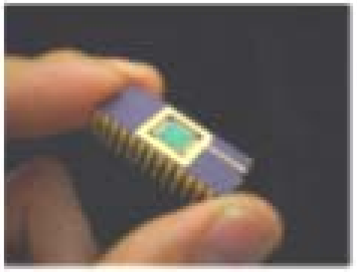
Long Channel Stick Transistors

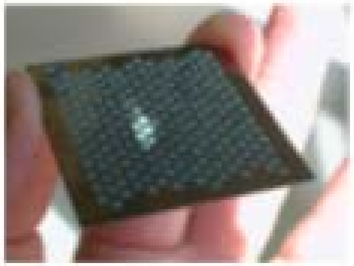


Conformal Solar Cells

Flexible Electronics

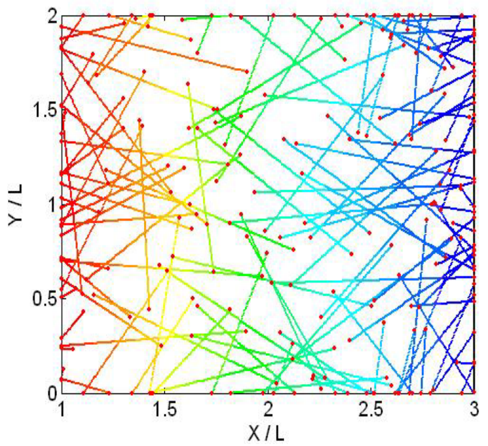


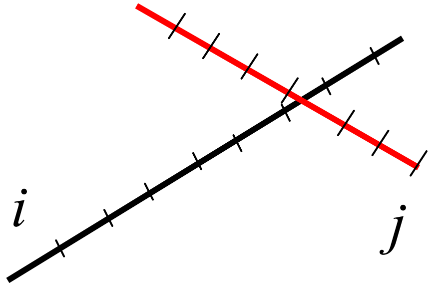
Memory



Drug Discovery Substrates

Nanosys Inc





$$J_i = q n_i \mu \frac{d\phi_i}{ds} + qD\frac{dn_i}{ds}$$

$$\frac{dJ_i}{ds} = a_{ij}(\phi_i - \phi_j) \text{ @ intersection}$$

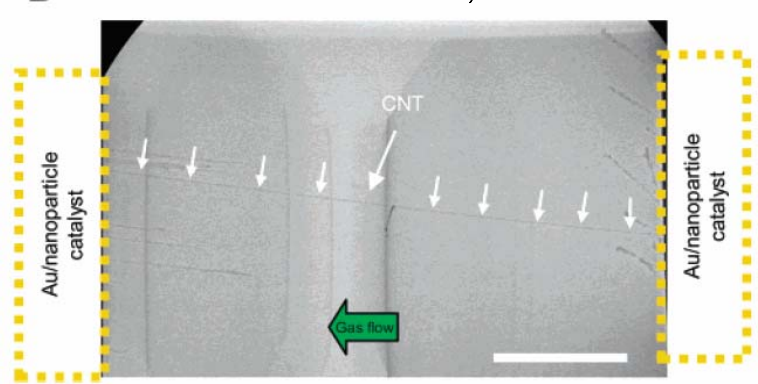
$$q n_i \mu \frac{d^2\phi_i}{ds^2} - a_{ij}(\phi_i - \phi_j) = 0$$

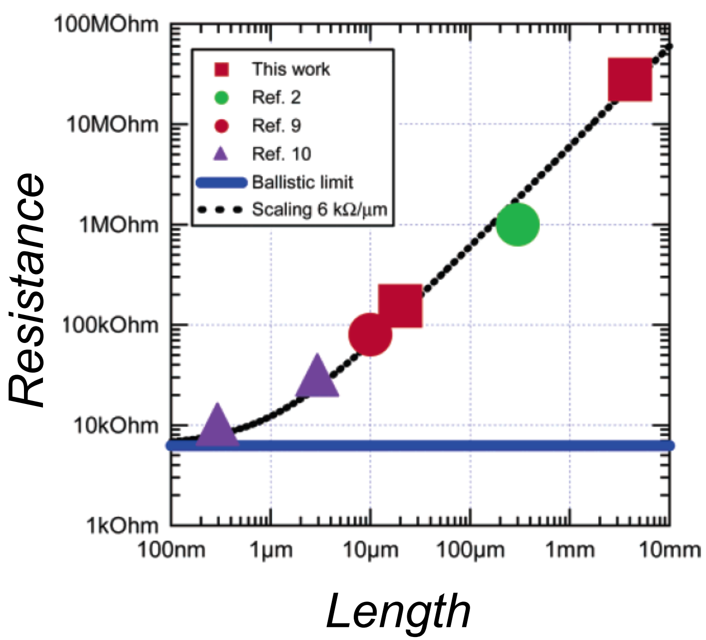
$$\frac{d^2\phi_i}{ds^2} - c_{ij}(\phi_i - \phi_j) = 0$$

$$C_{ij} = G_{mutual}/G_{self}$$

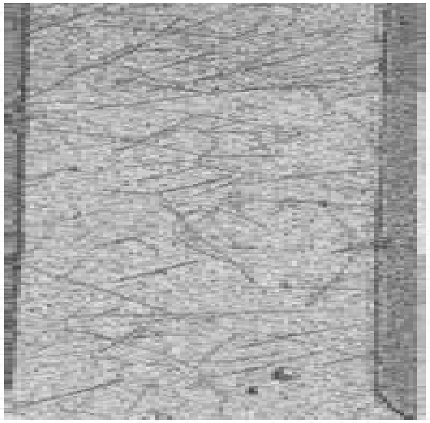
Self and Mutual Conductance

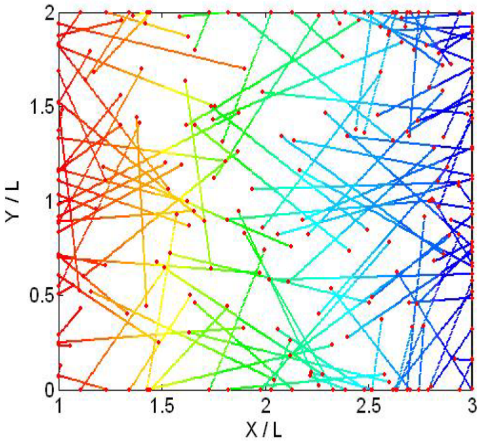
Li et al. Nanolett, 2004.





Algorithm





For each bias ….

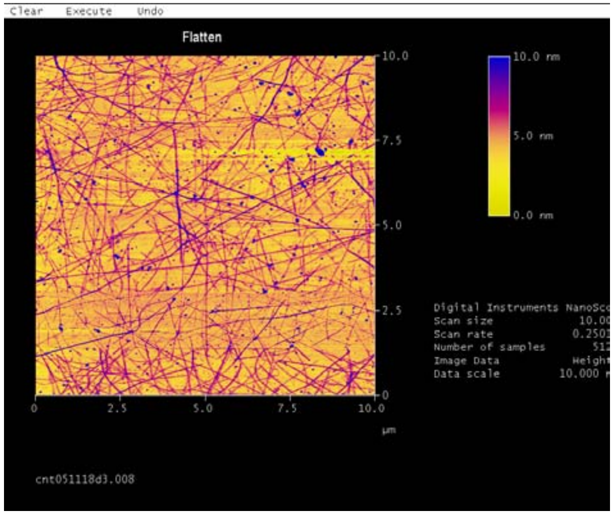
For each sample ….

- Generate sticks at random location
  Stick density equals measured density
- Construct data structure for all the intersection points and segment lengths
- Solve the electrical equations on this network with appropriate boundary condition
- Compute the current flow out of the Contact

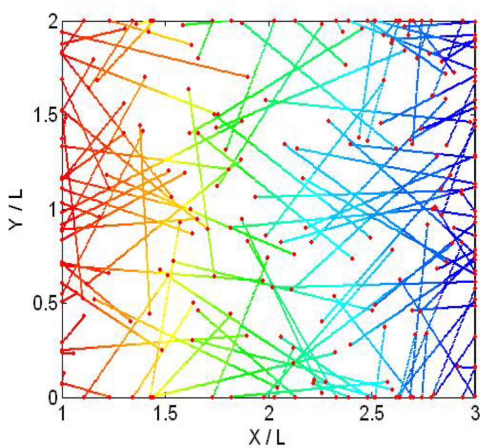
Repeat for 200 samples

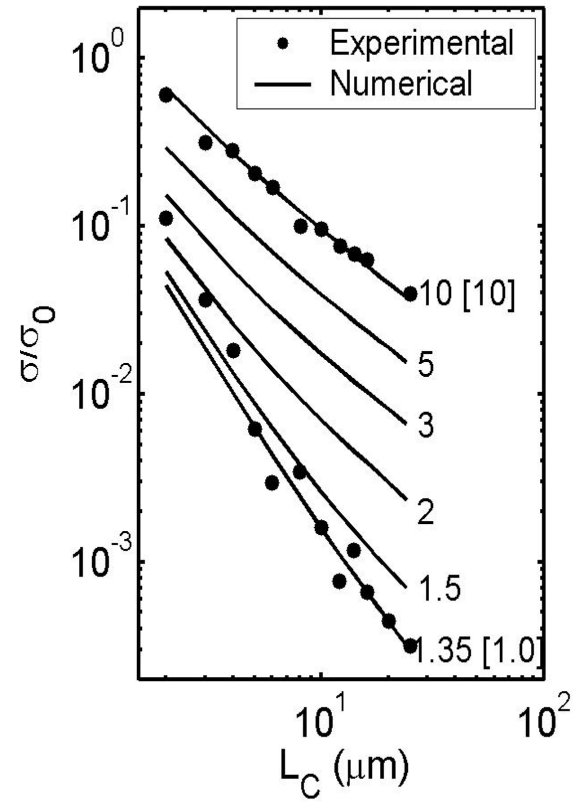
Repeat for all bias points

Length Scaling



Hines, Maryland

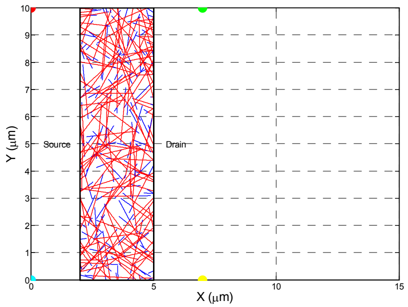


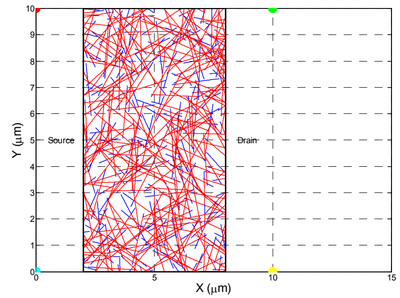


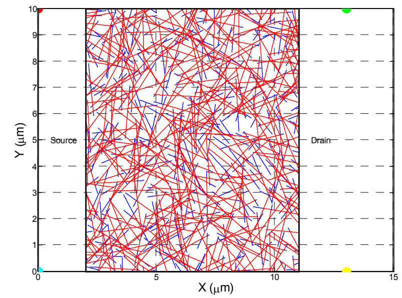
First known experimental verification of stick percolation

Experiment E. S. Snow *et al.*, APL **82**(13), 2145 (2003).
Simulation: S. Kumar *et al.*, PRL, **95**(6), 66802, (2005).

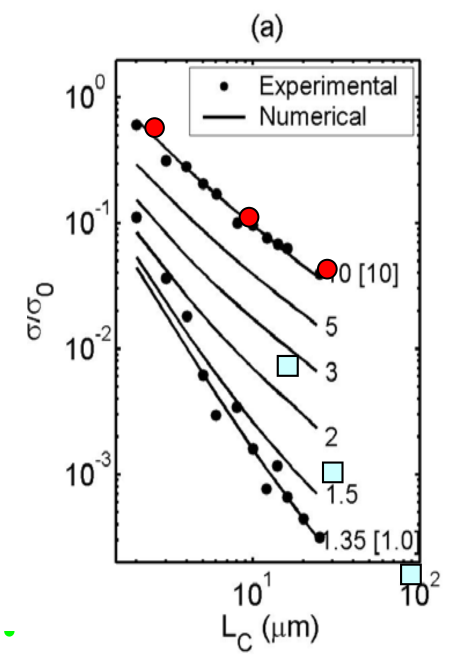
Current Scaling Near Threshold

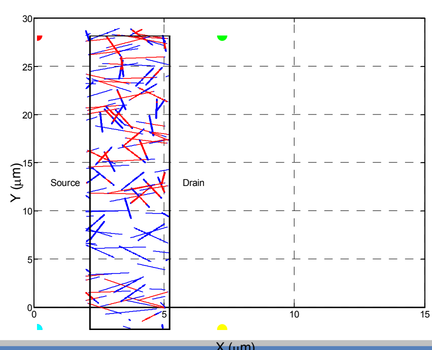


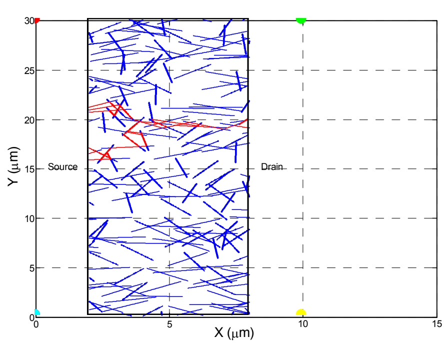


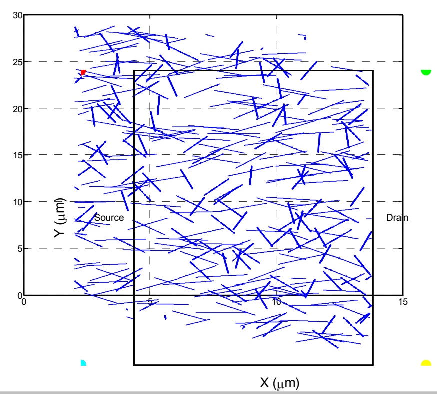


$$\frac{\sigma}{\sigma_0} = \frac{W_{eff}}{L_c}$$

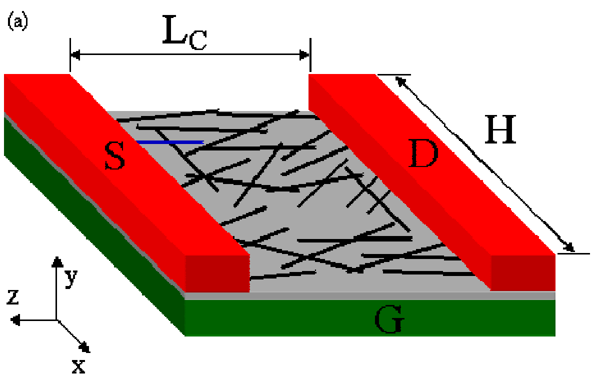


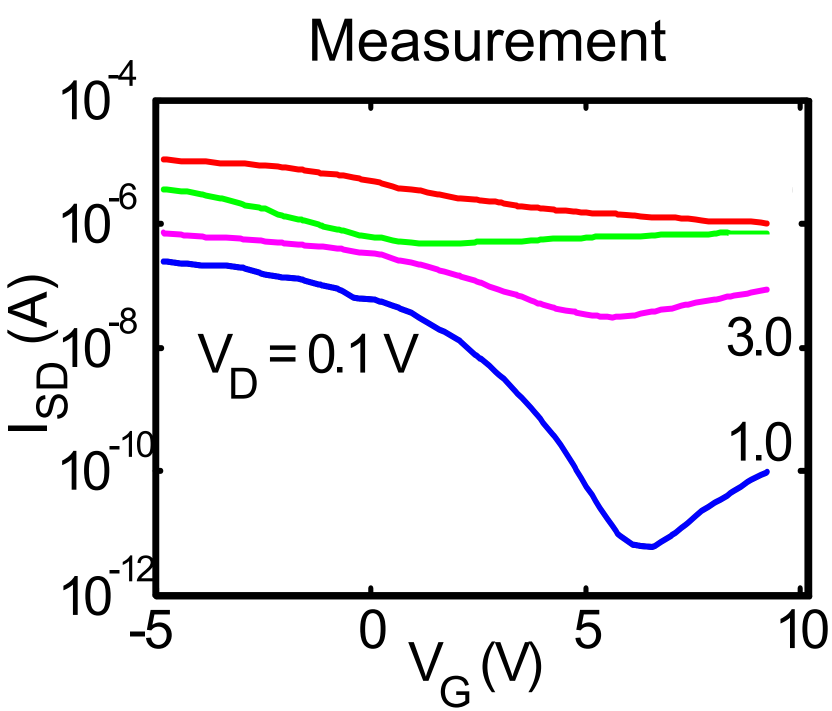






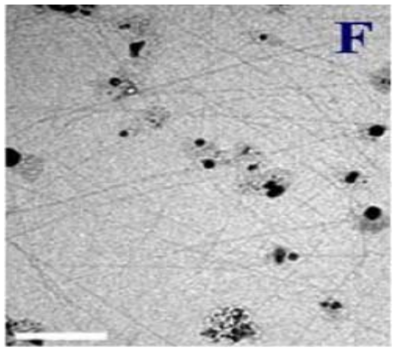
On-Off Ratio in Linear Regime

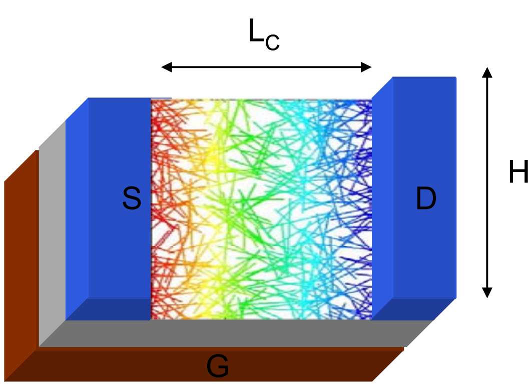


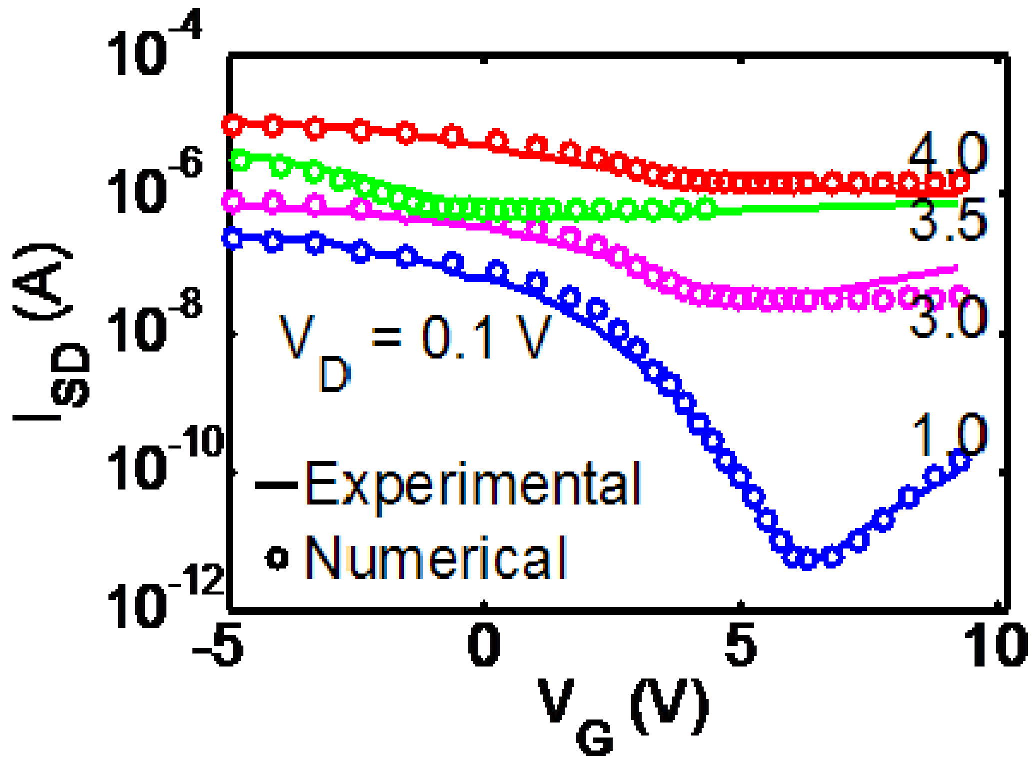


- ON/OFF ratio > 10^4 at low density
- Ratio changes dramatically at certain density
- Both ION and IOFF increases with stick density

Simulation & Measurement

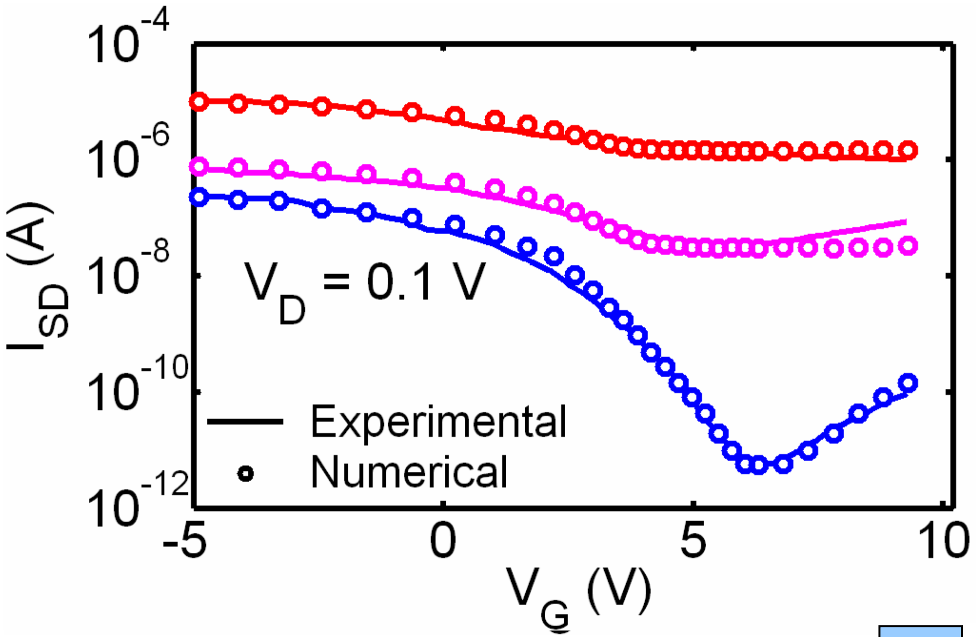




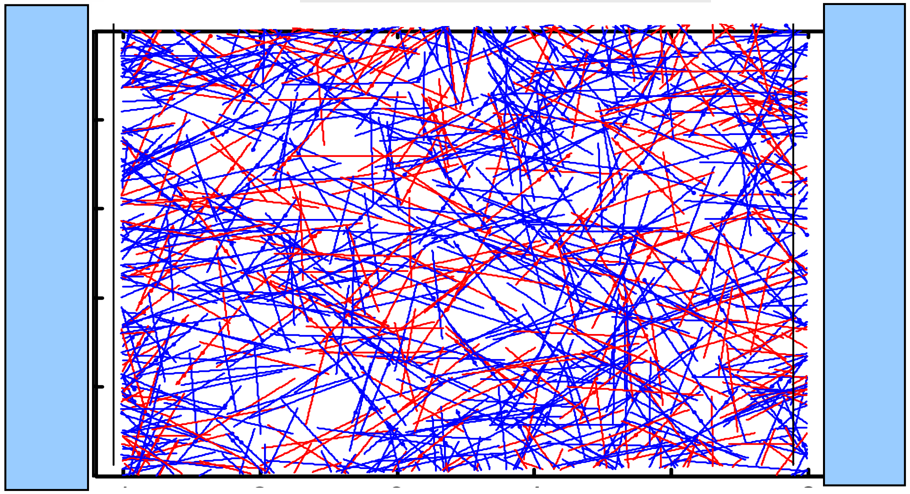


Excellent agreement between theory and measurement …

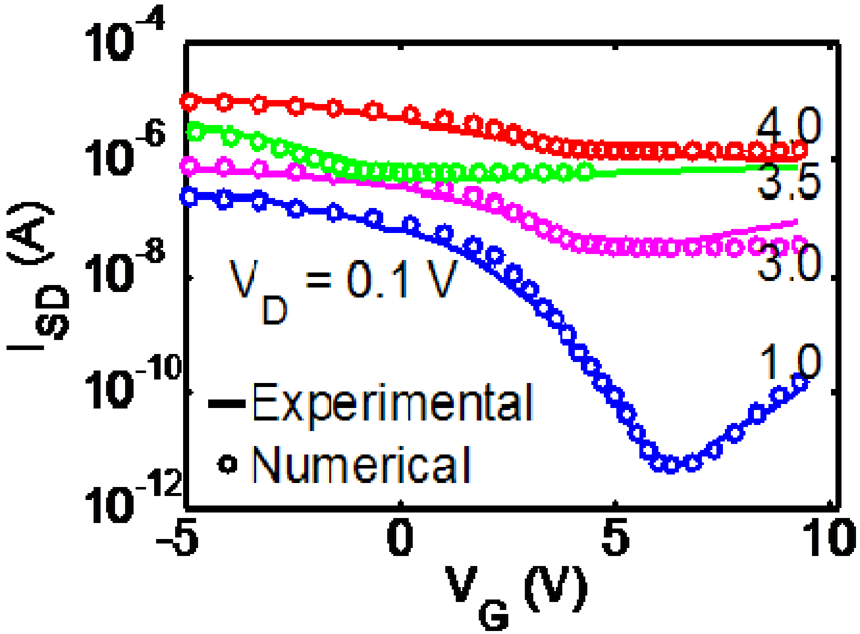
Modeling On-Off Ratio



$$\rho^{(S)} > \rho_{th}; \rho^{(M)} > \rho_{th}$$



Sub-threshold Slopes and Process Improvement



$$S = 2.3\frac{k_B T}{q}\left(1+\frac{C_Q + C_D + C_S + C_{IT}}{C_{OX}}\right)$$

$$\approx 2.3\frac{k_B T}{q}\left(1+\frac{C_{IT}}{C_{OX}}\right)$$

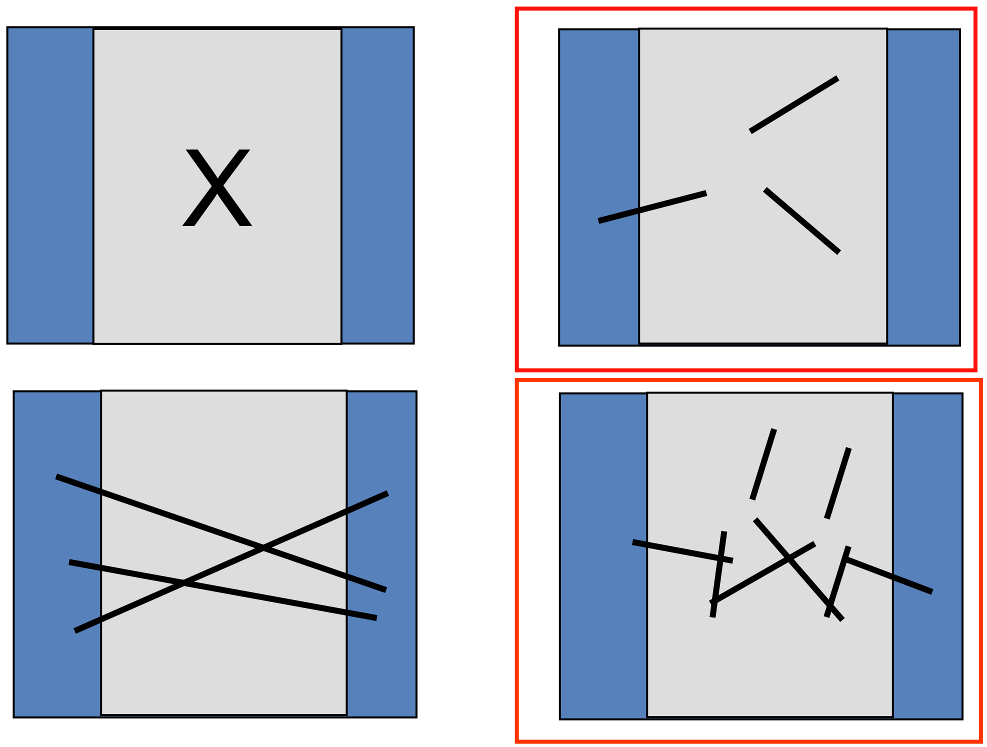
- 1/100 atoms is NIT (80-100 mV/dec vs. 800-1200 mV/dec
- Electrolyte gating helps, so does reduced Tox
- Very different from S of short channel devices
- Should focus on process improvement

Organics and Saturation in Part II

$L_S > L_C$ $\qquad$ $L_S < L_C$

$\rho < \rho_{th}$

$\rho > \rho_{th}$



- Organics
- Numerical
- *S. Kumar*

- Macroelectronics
- Numerical
- *S. Kumar & N. Pimparkar*

- Microelectronics
- Analytical Models
- *N. Pimparkar*

… and what if the tube are not randomly oriented ….

The simple framework of heterogeneous percolating network is sufficient to interpret wide range of NN-TFT physics

For microscopic Applications:

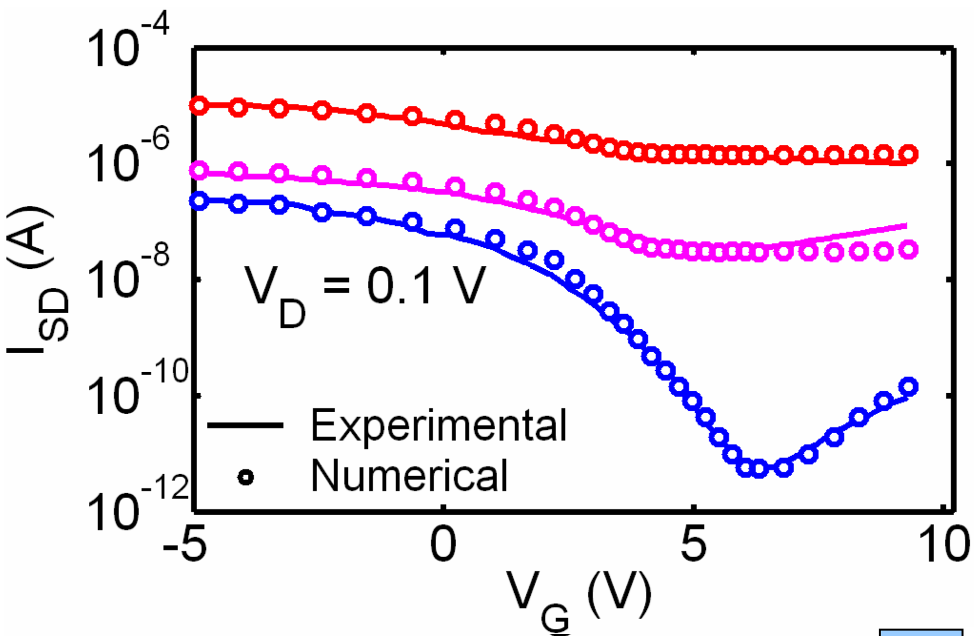
- Fan diagram allows intuitive analysis of many device characteristics
- Electrical filtering of metallic tubes dictates minimum Lc.
- Promising approach for high-current applications.

For macroscopic Applications:

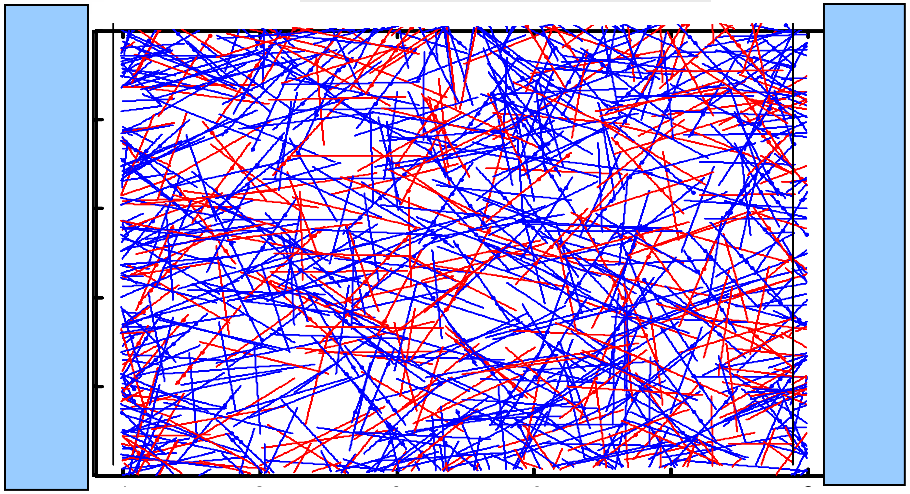
- Stick percolation interprets channel length dependence
- Electrical filtering is unnecessary for a optimal density.
- Interface traps is a serious concern for the technology.

Questions and Answers

Modeling On-Off Ratio

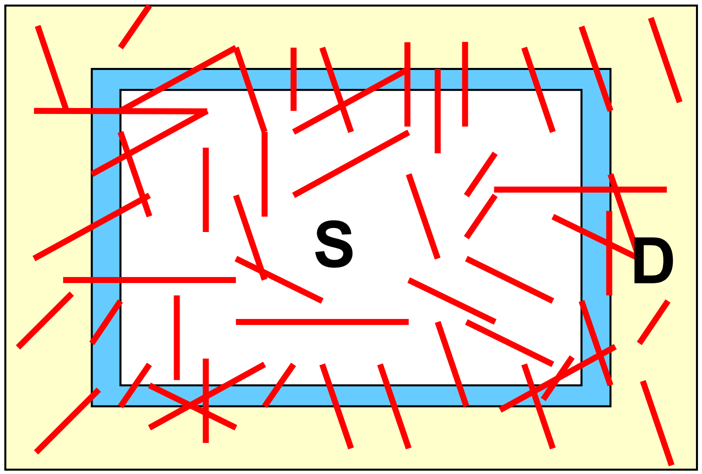


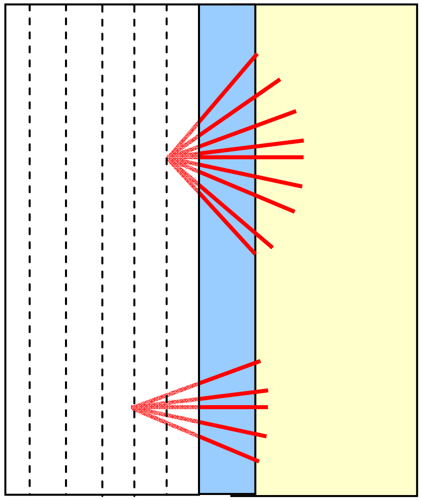
$\rho^{(S)} > \rho_{th}; \rho^{(M)} > \rho_{th}$

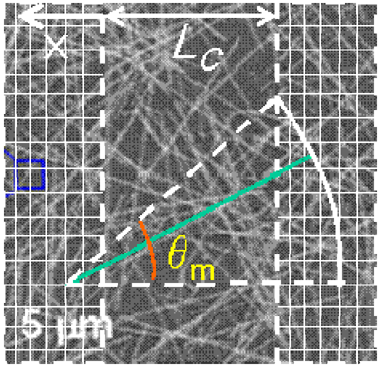


Low drive current, Site-specific Placement

Analysis by Fan Diagram!







Seidel et al., Nano Letters, 831, 2004

$$N_S = \sum_x \frac{\theta_m(x)}{\pi/2}$$

$$R_S = L_S / L_C$$

- *Generalized Buffon Needle Problem!*

$$= \frac{\pi D_x L_S}{2}\left\{\sqrt{1-R_S^{\,2}} - R_S \cos^{-1} R_S\right\}$$

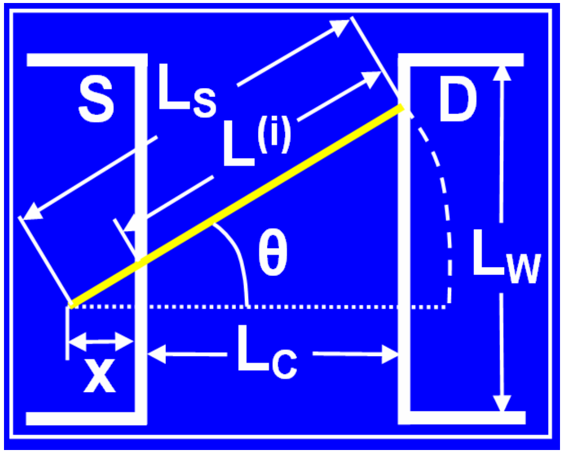
Analytical Model

- Ballistic Limit

$$\frac{I_B}{f_1(V_D,V_G)} = \sum_1^N 1 = \int_0^{\theta_{max}} 2D_C/\pi(L_S\cos\theta - L_C)d\theta$$

- Diffusive Limit

$$\frac{I_D}{f(V_D,V_G)} = \sum_1^N \frac{1}{L^{(i)}}$$



- Velocity Saturation

$$\frac{I_{sat}}{f(V_D,V_G)} = \sum_1^N 1$$

- Intermediate L_C

$$\frac{I_T}{f(V_D,V_G)} = \sum_1^N \frac{\lambda}{\lambda + L^{(i)}} = \int_0^{\theta_{max}} \frac{2D_C}{\pi}\frac{\lambda}{\lambda + L_C/\cos\theta}(L_S\cos\theta - L_C)d\theta$$

Theory:

- Prof. J. Murthy (ME),
- N. Pimparkar (EE) & S. Kumar (ME)

Experiments

- J. Rogers (UIUC),
- E. Snow (NRL), G. Blanchet (Dupont), P. Leon (Nanosys)

Support

- NCN, Agilent Technologies, Nanosys Inc.
- R. Ruess (DAPRA)