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ECE606: Solid State Devices
Lecture 40: Looking Back and Looking Ahead

Muhammad Ashraful Alam
alam@purdue.edu

Outline

1. **Looking Back: Quick review of what we learned**

2. New devices – looking ahead
   a. flexible electronics
   b. solar cells, and
   c. Nanobio sensors

3. Conclusion

Outline of the Course

Application specific device operation ← **Physical Principle of device operation** ← **Foundation in Physics**

↙ **Device-specific system design**

EE606

- TFT for Displays
- CMOS-based Circuits for μP
- LASERS for Disk Drives
- MEMS for Read heads

- Resistors (5 wk)
- Diodes (3 wk)
- Bipolar (3 wk)
- MOSFETs (3 wks)

Quantum Mechanics
+
Statistical Mechanics
↓
Transport Equations

Quantum, Statistical Mechanics to Devices

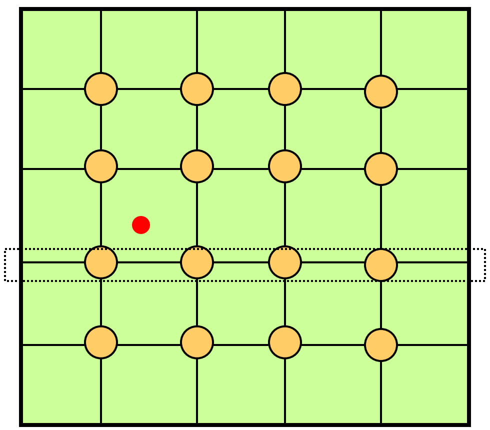
$$\left(m^*, E_g\right) + f$$

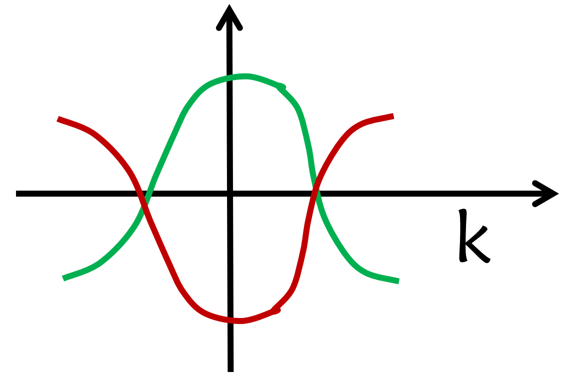
$$\rightarrow N_C, N_V, \mu, \tau$$

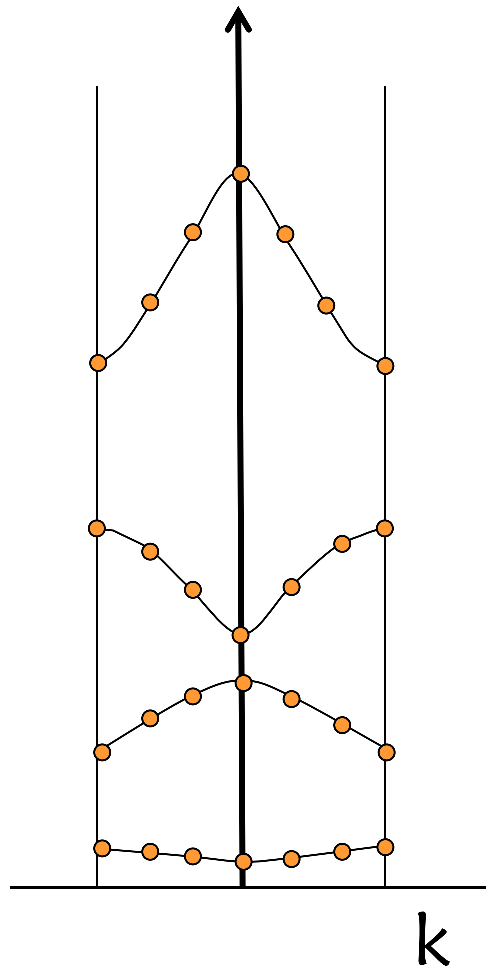
$$\rightarrow n \times p = n_i^2 e^{(F_n - F_p)\beta}$$

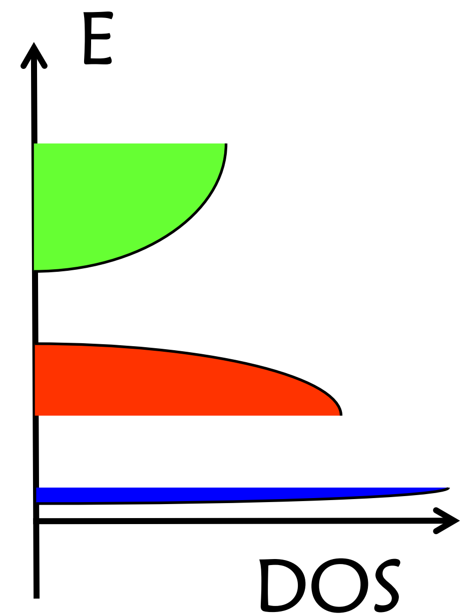
A Quick Summary

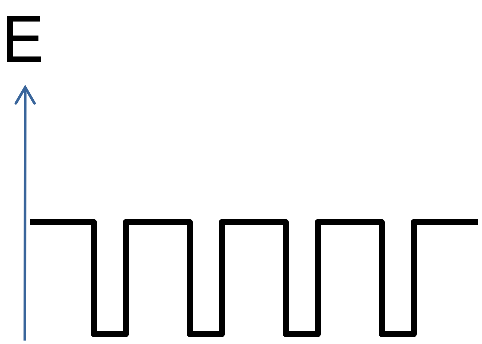
$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{d^2E}{dk^2}$$



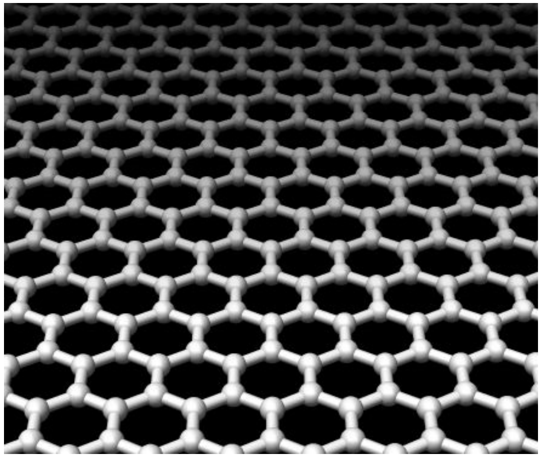




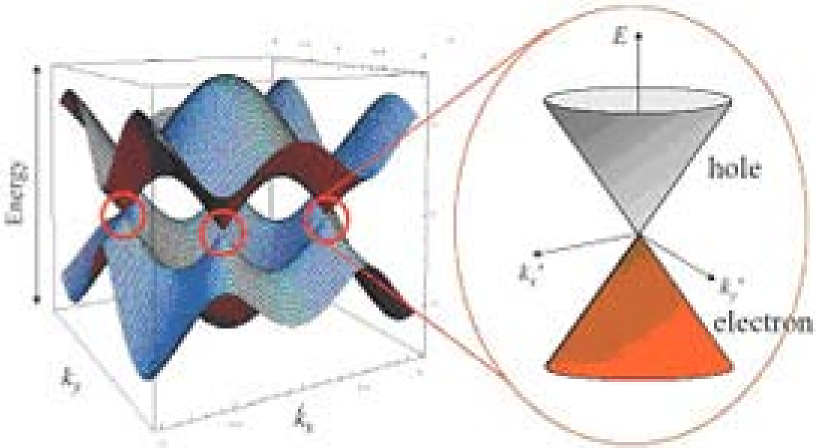




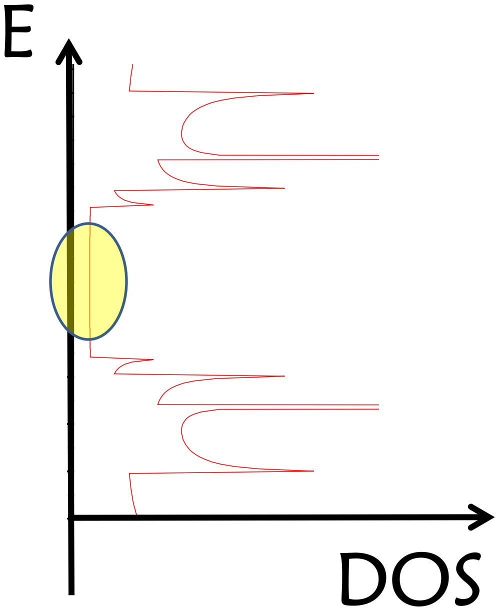
Graphene and other materials ..



$$\frac{1}{m^*} \neq \frac{1}{\hbar^2}\frac{d^2E}{dk^2}$$

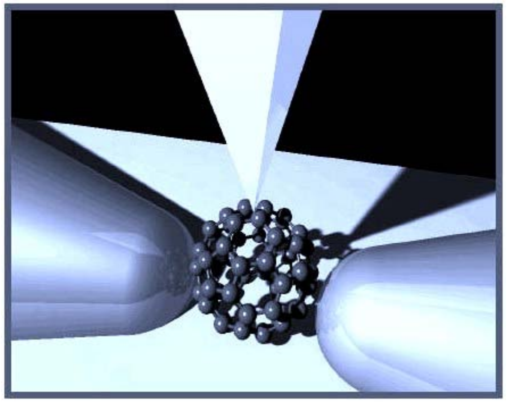


www.magnet.fsu.edu

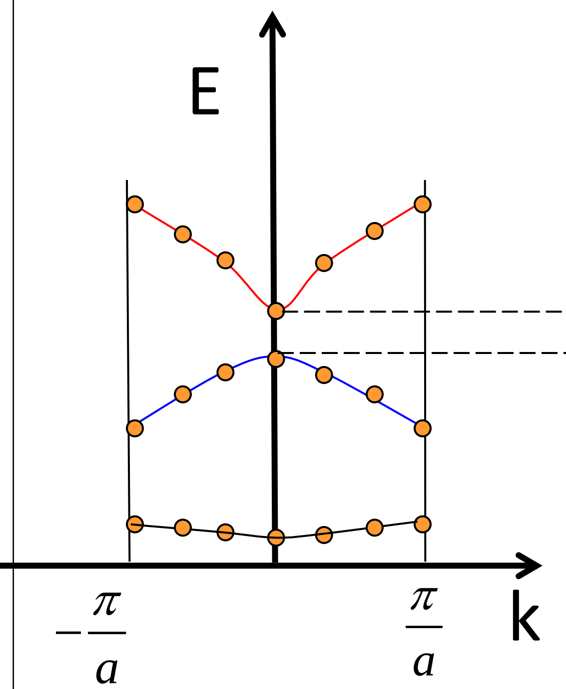


On Fermi Functions

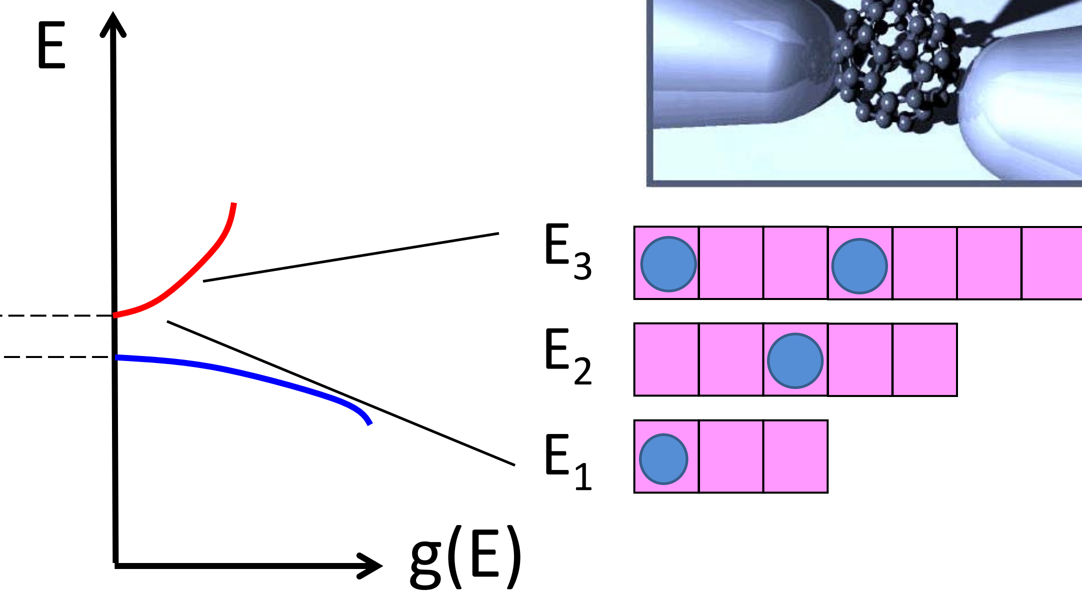
http://www.physics.mcgill.ca/SPM/JEOL/



Energy-Band



Density of States



$$f_D = \frac{N_D}{1 + g_D e^{(E_F - E_D)/k_B T}}$$

Importance of correlation – free vs. localized states

Equations to solve … analytical/numerical approach

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N \mathcal{E} + qD_N \nabla n$$

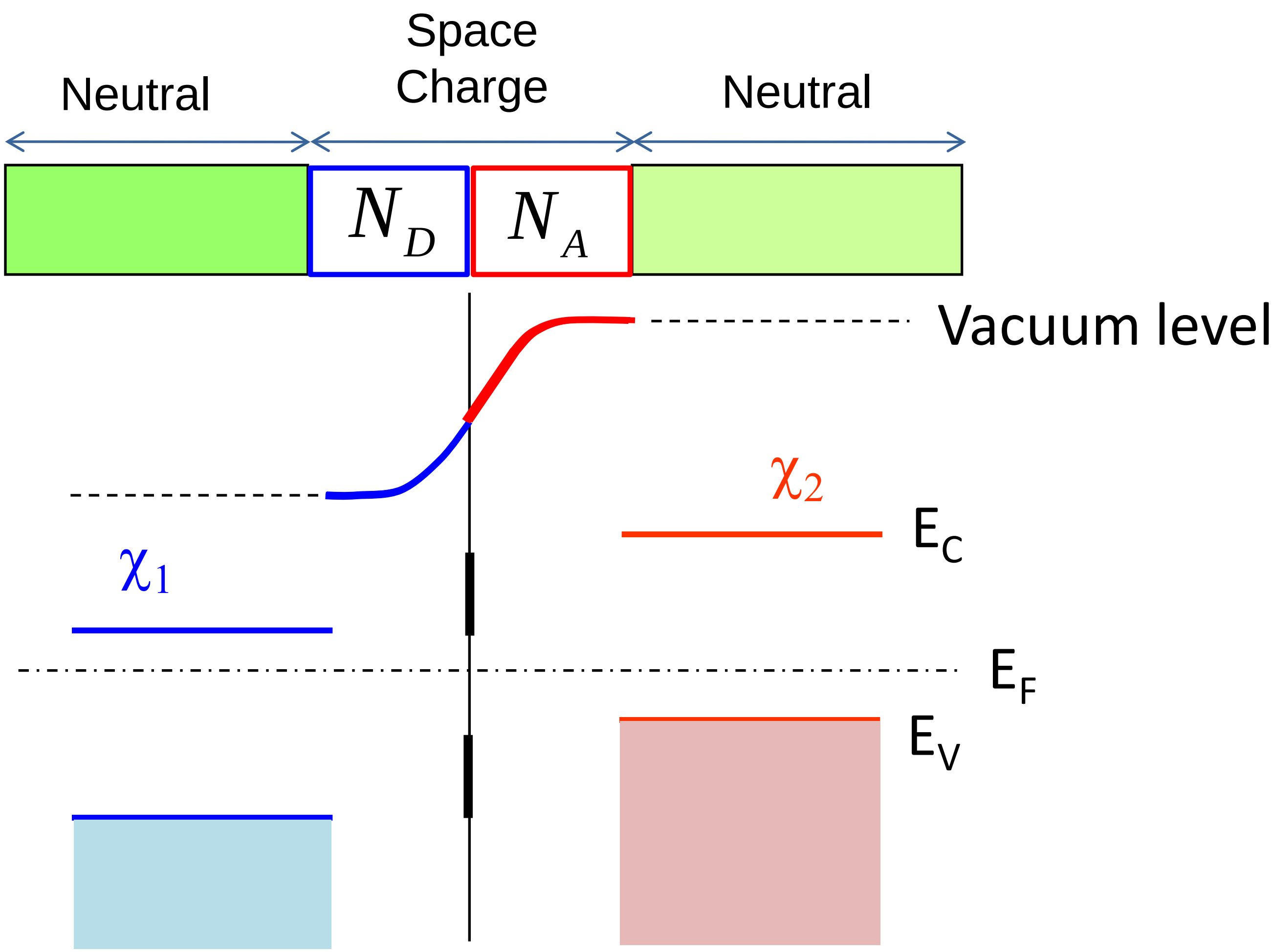
$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P \mathcal{E} - qD_P \nabla p$$

← Band-diagram

← Diffusion approximation,
Minority carrier transport,
Ambipolar transport

Short-cut to Band-diagram



… is equivalent to solving the Poisson equation

Minority Carrier Diffusion

$$\Delta n(0^+) = n(0^+)_{V_G} - n(0^+)_{V_G=0}$$

$$= \frac{n_i^2}{N_A}\left(e^{qV_A\beta} - 1\right)$$

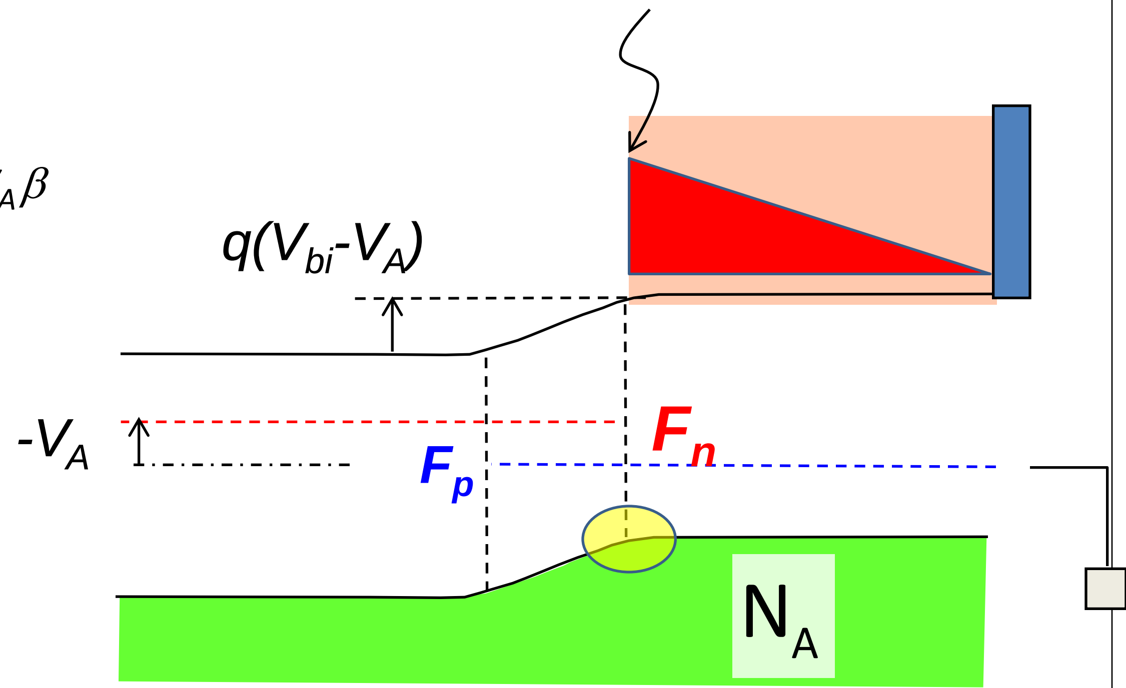
$$n(x=0^+) = n_i\, e^{(F_n - E_i)\beta}$$

$$p(x=0^+) = n_i\, e^{-(F_p - E_i)\beta}$$

$$np = n_i^2 e^{(F_n - F_p)\beta} = n_i^2 e^{qV_A\beta}$$

$$p(0^+) = N_A$$

$$n(0^+) = \frac{n_i^2}{N_A} e^{qV_A\beta}$$



Thermionic Emission & Heterostructure Discontinuity

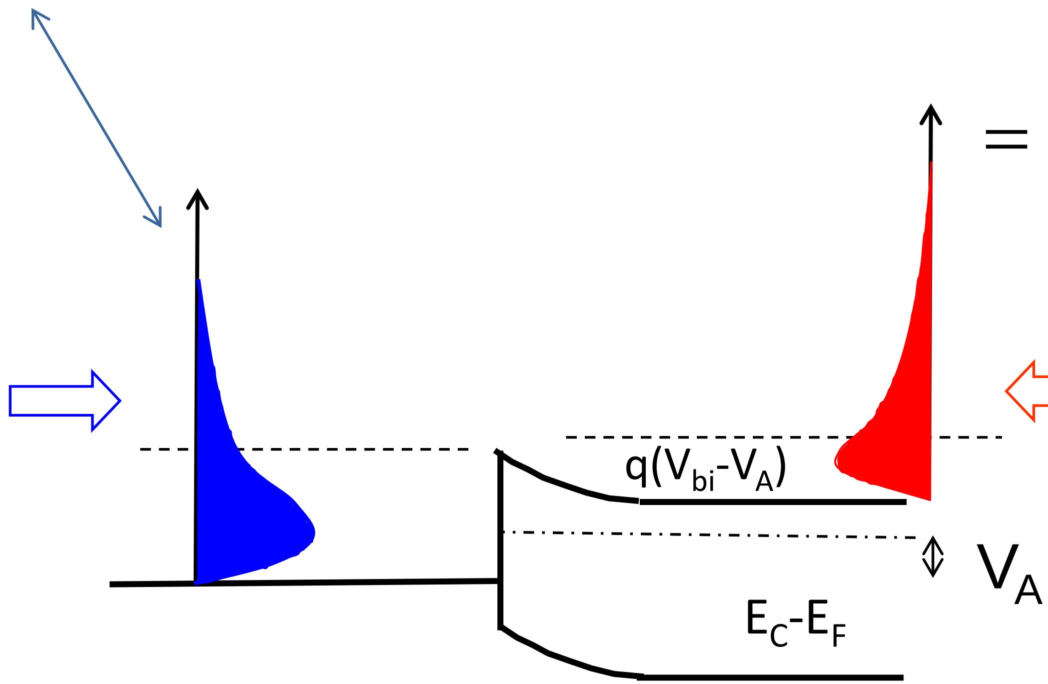
$$J_T(V_A) = J_{m\to s}(V_A) - J_{s\to m}(V_A) = J_{m\to s}(0) - J_{s\to m}(V_A)$$

$$J_{m\to s}(V_A) = -q\frac{n_m}{2}e^{-\frac{q\Phi_B}{kT}}\upsilon_{th}$$

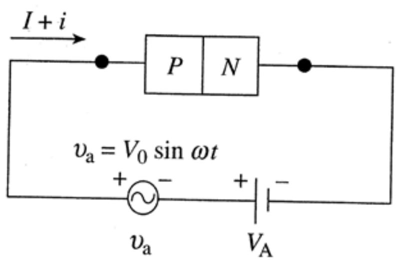
$$J_{s\to m}(V_A) = -q\frac{n_s}{2}e^{-q\frac{V_{bi}-V_A}{kT}}\upsilon_{th}$$

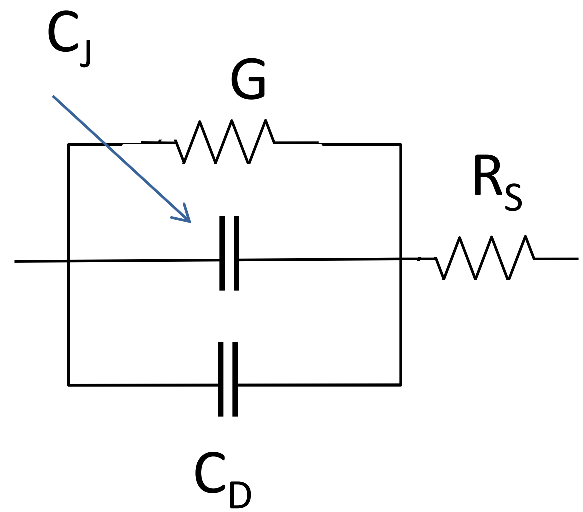
$$= -q\frac{n_s\upsilon_{th}}{2}e^{-\frac{qV_{bi}}{kT}}\times e^{\frac{qV_A}{kT}}$$

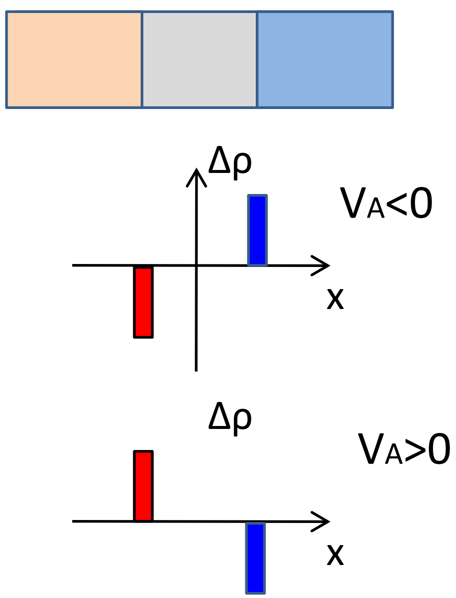
$$= -q\frac{n_m\upsilon_{th}}{2}e^{-\frac{q\Phi_B}{kT}}e^{\frac{qV_A}{kT}}$$

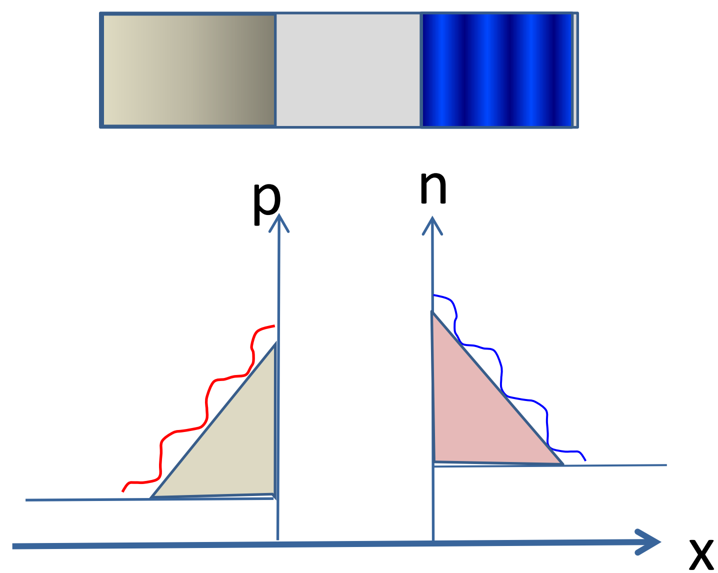


Small Signal AC Response

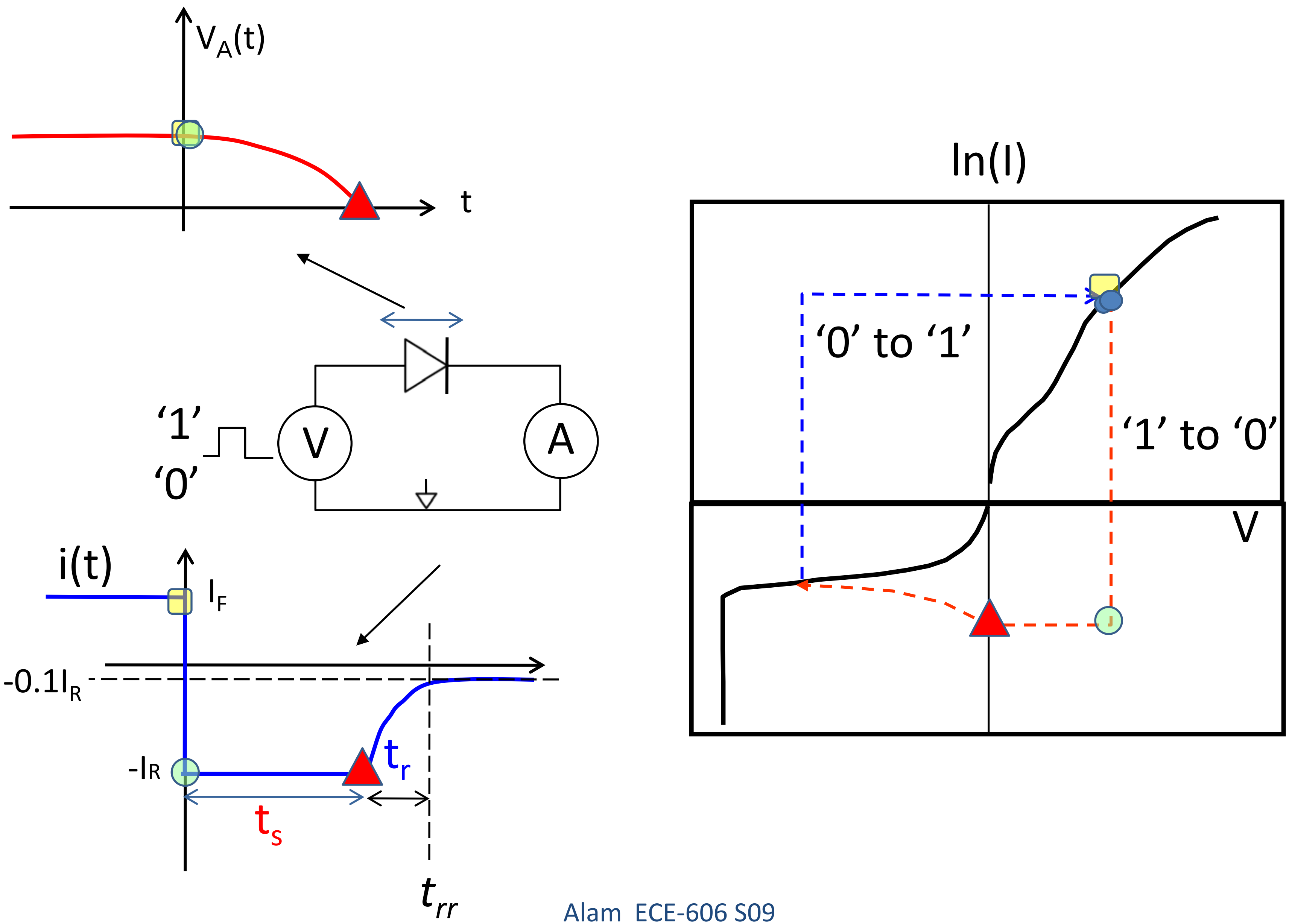






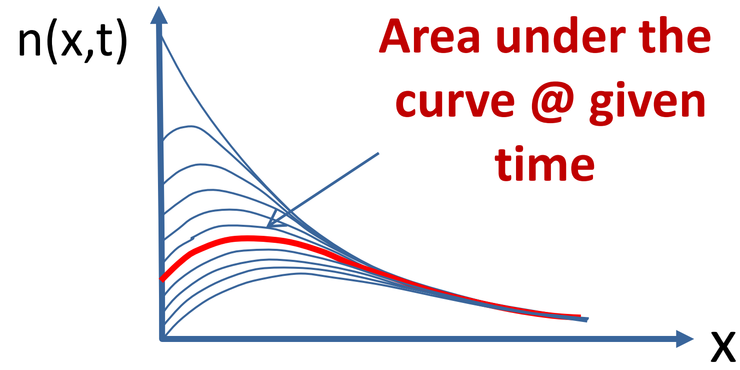


Digital, Large Signal Applications



Large Signal Charge Control Model

$$\frac{\partial(\Delta n)}{\partial t} = D_N \frac{d^2(\Delta n)}{dx^2} - \frac{\Delta n}{\tau_n}$$



$$\int_0^{W_p} \frac{\partial(qA\Delta n)}{\partial t} dx = \int_0^{W_n} D_N \frac{d}{dx}\frac{d(qA\Delta n)}{dx} dx - \int_0^{W_n} \frac{qA\Delta n}{\tau_n} dx$$

$$\frac{\partial Q}{\partial t} = D_N \left.\frac{d(qA\Delta n)}{dx}\right|_{x=W_p} - D_N \left.\frac{d(qA\Delta n)}{dx}\right|_{x=0} - \frac{Q}{\tau_n}$$

$$Q \equiv \int_0^{W_p} (qA\Delta n)\, dx$$

$$\frac{\partial Q}{\partial t} = i_{diff} - \frac{Q}{\tau_n}$$

Few concepts for Device Analysis

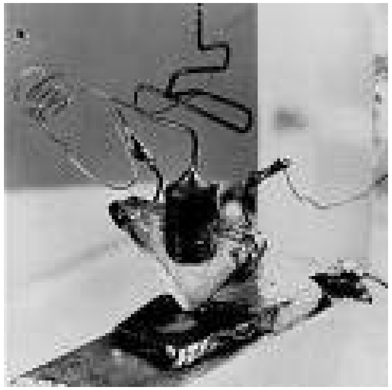
	Equilibrium	DC	Small signal	Large Signal
Diode	Band-diagram	diffusion	dn/dt~jωn	Charge-control
Schottky	Band-diagram	TE	Junction capacitance	Majority transport
BJT/HBT	Band-diagram	diffusion /TE	dn/dt~jωn	Charge-control
MOSCAP MOSFET	2D band-diagram	Drift/TE	MOS capacitance	Charge-control

Grand Challenges in Electronics

Vacuum Tubes

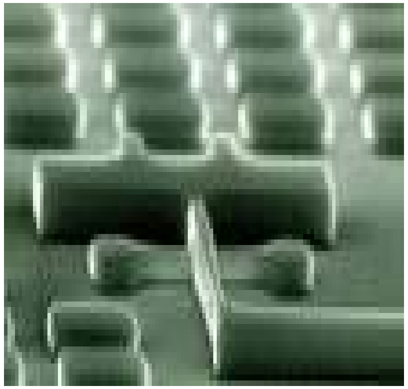
1906-1950s

Bipolar



1947-1980s

MOSFET



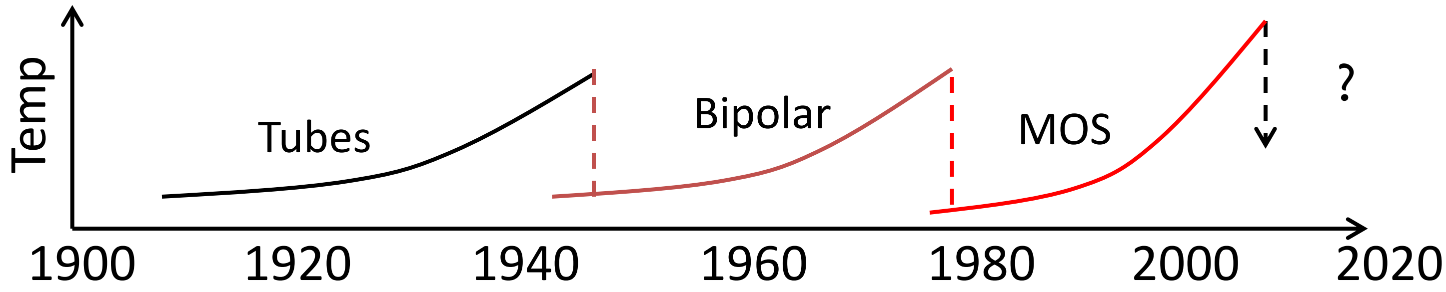
1960-until now

Now ??

Spintronics

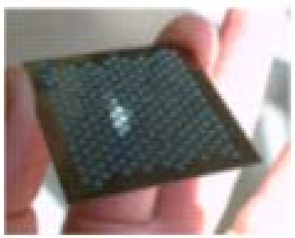
Bio Sensors

Displays ....



Emergence of Macroelectronics

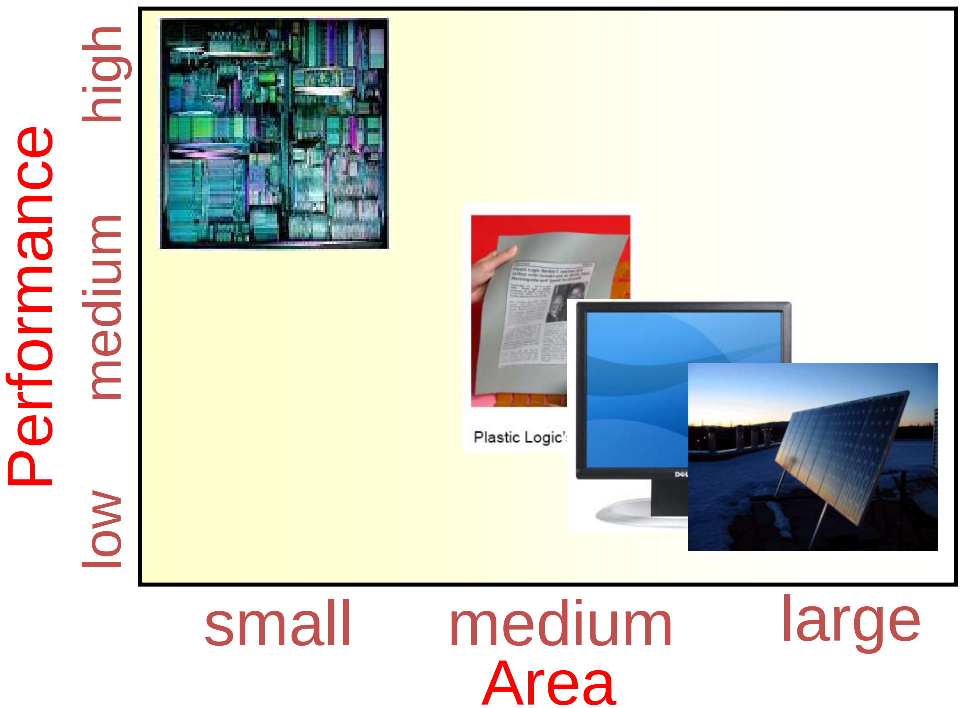
Biosensors Energy Flexible Electronics



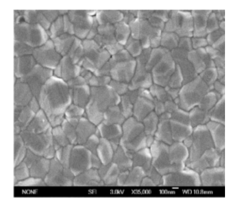
Drug Discovery Substrates

Conformal Solar Cells

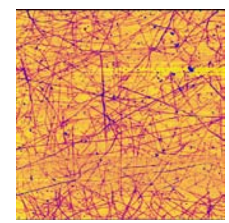
Flexible Electronics



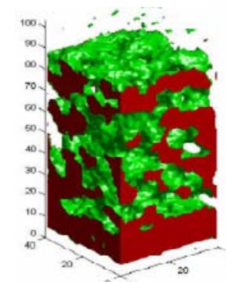
Poly-Si



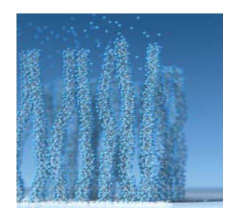
NanoNet



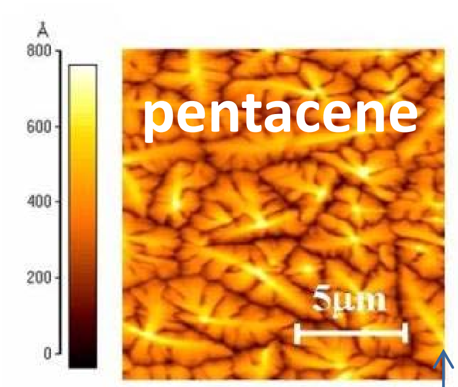
Polymers



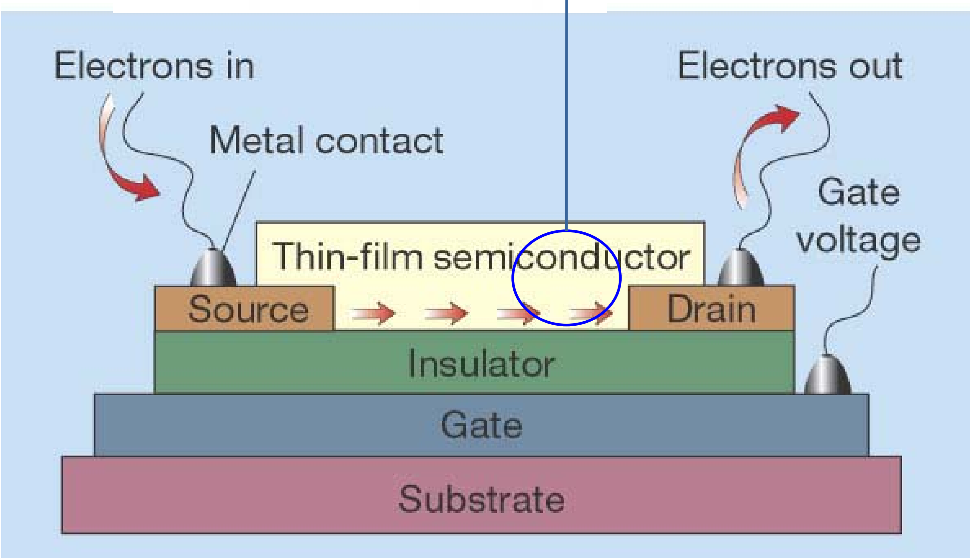
mesoporous



Thin Film Organic Transistors



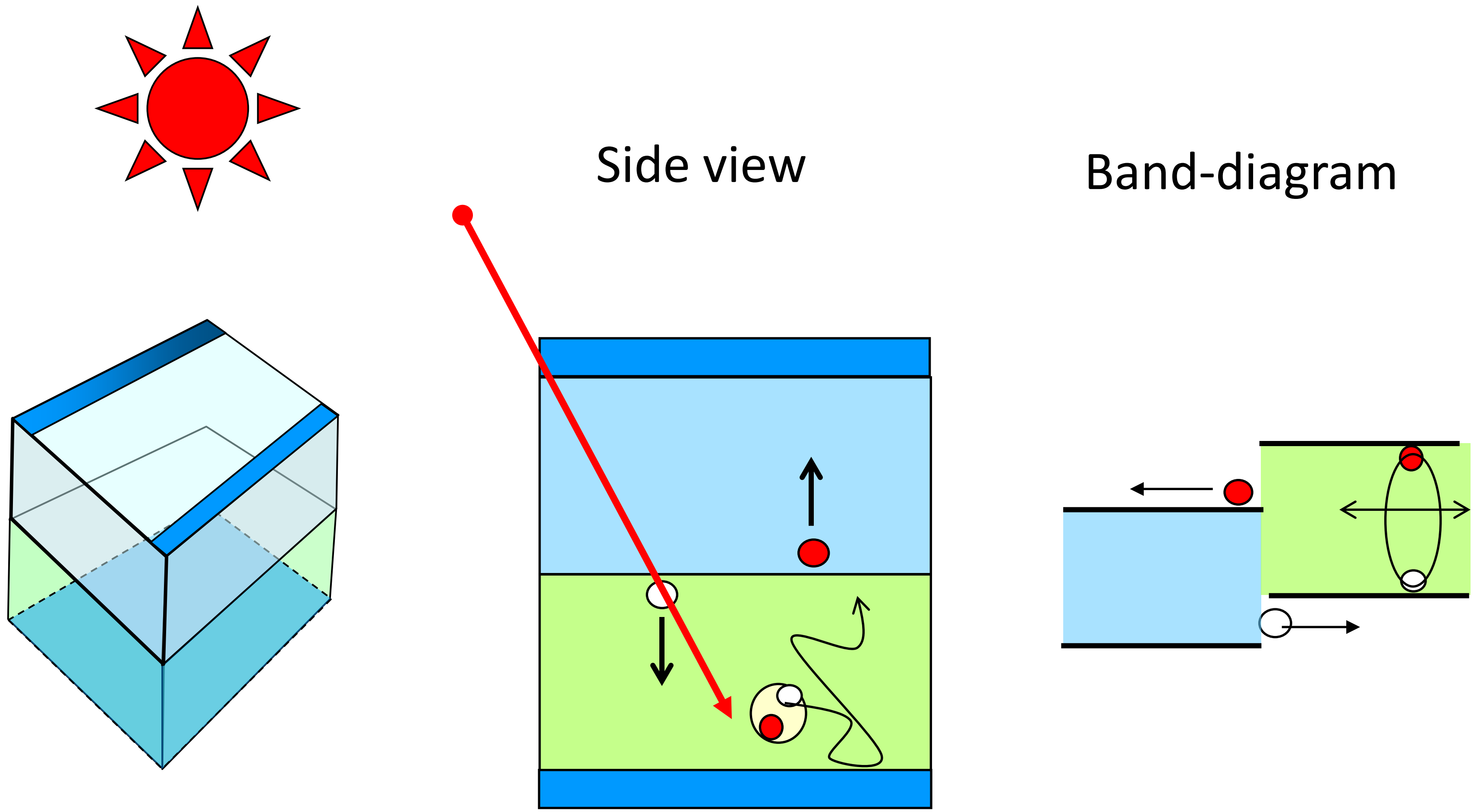
- Can you draw the band-diagram?
- What type of transport theory would you use?
- Would you be able to use numerical simulators from nanohub.org to explore the TFT?



Sony display 180x120 pixels

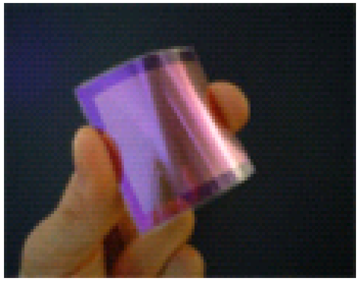
www.faculty.iu-bremen.de/dknipp/group/research.htm
M.G. Kanatzidis, Nature, 428, 2004.

Four processes of a Solar Cell



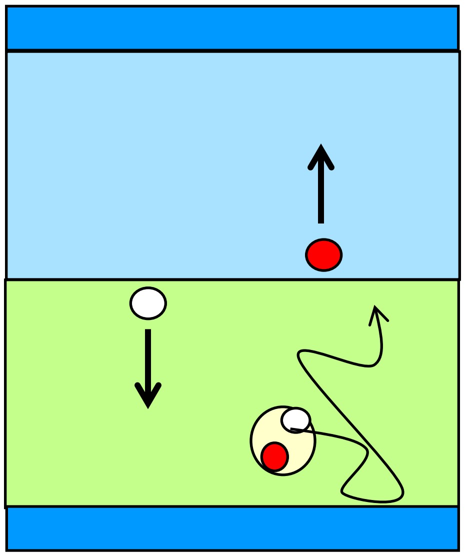
Electron-hole recombination before dissociation at the junction makes it a poor cell ...

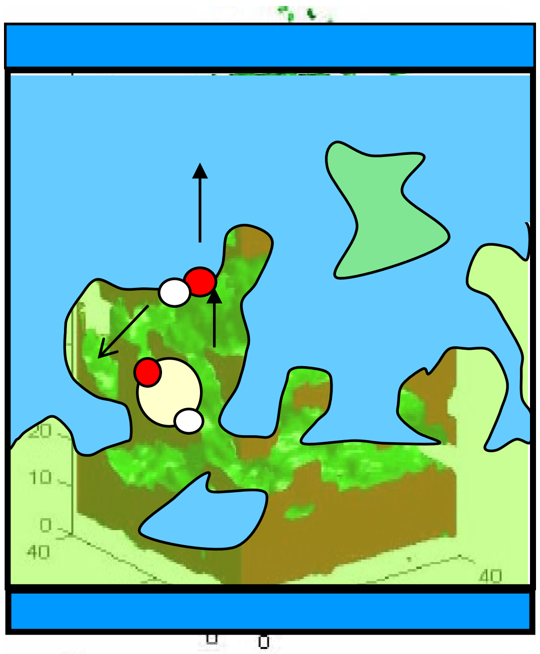
Nanostructured Solar Cells

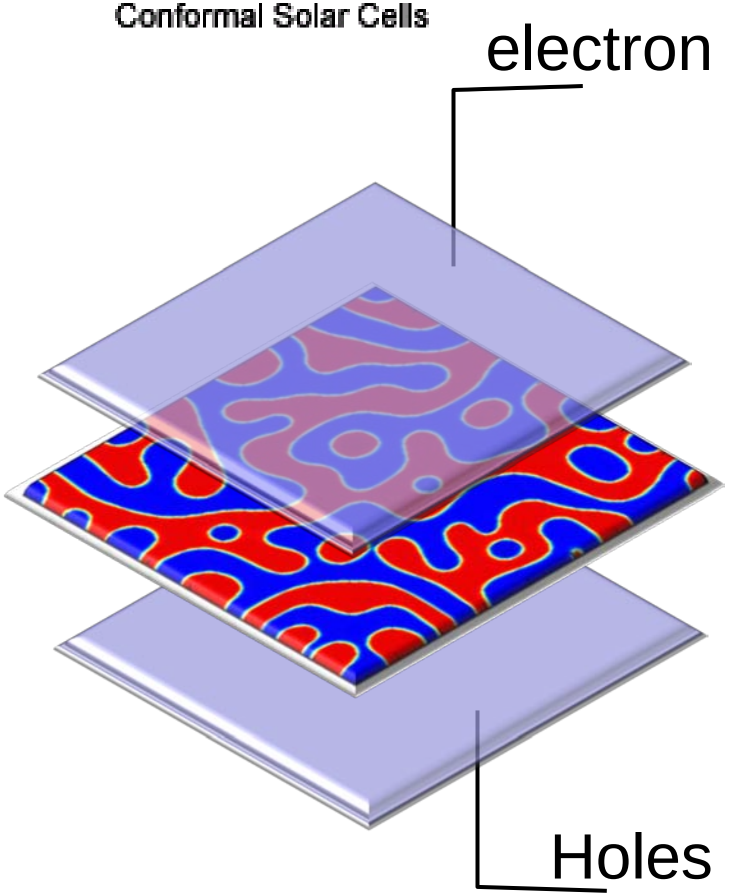


Conformal Solar Cells

mixed layers

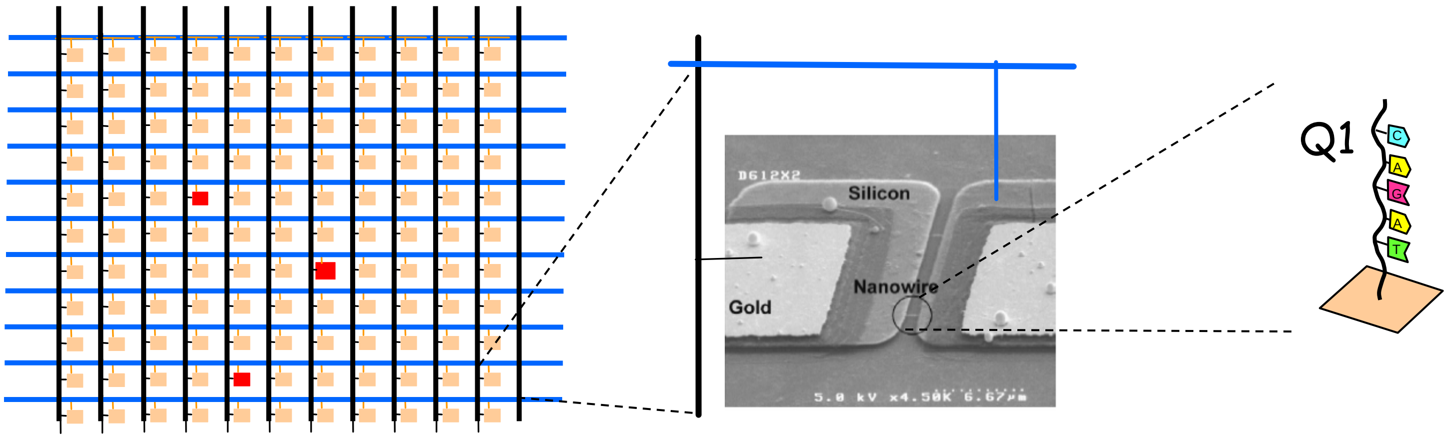


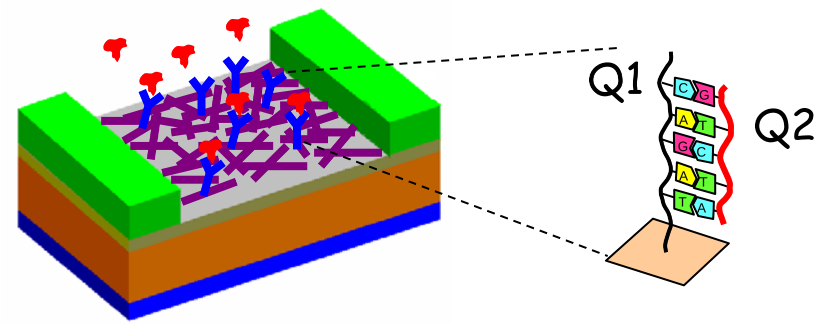


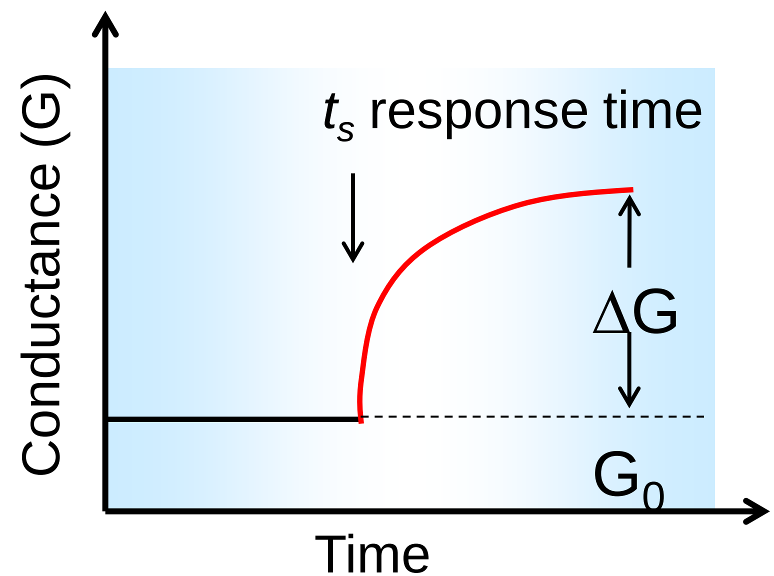


Fundamentals of nanobiosensing

An array … Individual sensor Capture Probe







Optical detection schemes

Surface Plasmon Resonance

Conclusions: Robots and Jellyfish

Resources

energy

function

reusability

Life at the edge of equilibrium thermodynamics is very successful ; Shouldn't our electronics be the same ?

Summary

1) Electronics remains a vibrant area and there have been many innovation beyond the classical electronic devices.

2) It is likely that electronics will find applications beyond computing and communication. Nothing new, actually! Electronics started with electrical machines, branched into communication, radar, then to computing; future applications in energy conversion, health care are anticipated.

Acknowledgement

1) Mohammad Asaduzzman for help with figures and HW.
2) Mr. Joe Cychosz and Rick DeSutter for helping us videotape these lectures.
3) Network of Computational Nanotechnology for resources and Intel for financial support.
4) Profs. M. Lundstrom and S. Datta for discussions.
5) Students from previous EE606 classes who endured the course without lecture notes.
6) And to you … for showing up at 7:30am morning class!