Nanophotonics

- What is it?

- What does it really mean?
What is nanophotonics

- Photonics – Study and the use of light-matter interaction. For example, the study of the interaction between light and electrons in ruby crystal leads to the first laser.

- Nanophotonics – Study and the use of photonics in nanoscale materials or technologies.
  - For example optical properties of quantum dots
  - For example the use of photonics in nanoscale CMOS processing or nano-resolution microscopy.
When do we care about nano?

- When the length scale is $\ll$ optical wavelength $\rightarrow$ Nano!
  - E.g. near field (evanescent waves, surface EM mode, …)

- When the interaction takes place within a nano length scale
  - E.g. photonics in quantum dots and nanowires
Nanofabrication

Top-down (Miniaturization)
- Electronics circuits (IC)
- Photonics (e.g. lasers)

Bottom-up
- Putting small things together
- Individual manipulation of atoms and molecules

Nanofabrication
Some reminders for you to take away

- Nanophotonic devices are not necessarily in the nano scale.
  - E.g. the photonic crystal device, quantum dot lasers, …

- Always keep in mind what applications you are looking for. Nano is not always “the” solution. For example surface plasmonic wave can be a useful tool for biosensing but still poses great challenge in chip-scale communication due to large loss.
Nanofabrication

- There are many potential technologies.

- But be careful when judging or comparing different technologies. Be fair in benchmarking process and keep in mind that the “current” technology also will improve!
Some recap

- The interaction of light and matters can be described by the **macroscopic** version of Maxwell’s equations if the length scale that we’re interested is > 10 nm.

- For dielectric media, the only quantity we need to determine to fully describe the interaction between light and matters is the dielectric constant $\varepsilon(r)$. 
Determination of $\varepsilon(r)$

- We only need to measure (or calculate) $\varepsilon(r)$ around resonances of basic excitations in the media. Then we can use Kramers-Kronig relation to evaluate the rest.

- Basic excitations:
  - Plasmons (free electron gas in metals or semiconductors)
  - Phonons (vibration of lattice)
  - Excitons (electron-hole pairs)
Lecture 2-6:

- Behavior of EM waves with known \( \varepsilon(r) \) in both near field and far field \( \rightarrow \) described by dispersion curve \( (\omega \text{ vs } k) \)

Lecture 7-10

- Different excitations and their implications on \( \varepsilon(r) \)
Quantum confinement

- The change of quantum confinement on electrons and holes leads to the change of the exciton behaviors $\rightarrow$ change in $\varepsilon(r)$

![Diagram](image-url)

3D 2D 1D 0D

$g(E)$ $g(E)$ $g(E)$ $g(E)$

$E_g$ $E$ $E_g$ $E$ $E_g$ $E$ $E_g$ $E$
Scanning Near-field Optical Microscope

Light wavelength (\(\lambda\)) 500 nm

- **Probe:**
  - aperture size (\(a\)) 25-100 nm
  - evanescent field \(a/\pi\)
  - tip-sample gap 5-50 nm

- **Sample:**
  - feature size < \(\lambda\)
  - skin depth \(0-\infty\)

- **Optics:**
  - Far-field detector 1-100 nm
  - Interference effects \(\lambda/4\)

![Image of Scanning Near-field Optical Microscope](image)

Transmission (\(\lambda=488\text{nm}\))

Fluorescence (\(\lambda>515\text{nm}\))
Surface plasmon polariton (SPP) confinement

Most of the energy is confined in the dielectric side.
Bio sensing

Figure 9.25. Surface plasmon resonance sensor schematic utilizing a CCD or photodiode array (left). The inset on the right-hand side shows the sensorogram. The top in the inset shows a shift in the SPR curve from 1 to 2 upon binding with the analyte. The bottom curve is obtained by monitoring the SPR signal at the shifted coupling angle as a function of time when the analyte is introduced. (Reproduced from http://chem.ch.huji.ac.il/~eugeniik/spr.htm.)

Ref: Prasad, Biophotonics, figure 9.25.
Dispersion engineering

- The spatial dependence of $\varepsilon(r)$ changes the propagation of EM waves and therefore changes the dispersion relation.
  - For example:
    - 1-D Bragg gratings
    - Photonic crystals

- The change in the basic excitation behavior changes the dispersion relation too.
  - For example:
    - EIT
    - population oscillation
EIT and slow light

Light speed reduction to 17 metres per second in an ultracold atomic gas

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\[ \omega_p = \omega_{31} \]

\[ \omega_s = \omega_{21} \]

1

3

2

slow light region

\[ T = 400 \text{ nK} \]

\[ \tau_{\text{FWHM}} = 7.05 \pm 0.05 \mu\text{s} \]

\[ L = 220 \pm 3 \mu\text{m} \]

\[ v_0 = 32.6 \pm 0.5 \text{ m s}^{-1} \]
Different approaches

- Top-down (litho/etch)
Different approaches

- Top-down (damascene/CMP)
Different approaches

- Top-down (liftoff)
Different approaches

- Bottom-up (strain-induced self-assembly)

\[ \Gamma = \frac{\Delta E_{\text{dis}}}{\Delta E_{\text{surf}}} \]

Q: amount of deposited material
CI = coherent islands
DI = dislocated islands
UF = uniform film
Different approaches

- Bottom-up (catalyst-induced self-assembly)
Different approaches

- Hybrid (selective-area growth)
Different approaches

- Hybrid (patterned substrate overgrowth)
Different approaches

- Hybrid (separate assembly)

http://www.mtmi.vu.lt/pfk/funkc_darini ai/nanostructures/nanotubes.htm
Lithography

- Optical wavelength determines the fundamental limit on resolution but not the minimum feature size.

- Optics + resist + etch determines the patterning performance.

- Many RET have been developed to enhance the performance.
Thin film deposition

- MOCVD, MBE, and ALE are three major technologies that are capable of depositing defect-free single crystalline materials with the atomic-layer precision on thickness control.
Self-assembled growth

- More flexible in growth conditions
- Hard to control size, location, and physical orientation
In addition to miniaturization…

- Technology is meant to improve our life experience and fulfill our curiosity for exploration.

- In addition to making the device smaller and smaller, we also need to focus on several key parameters:
  - Human interface (portability, accessibility, etc)
  - Multi-functionality (e.g. SOC-MT)
  - Lower power consumption
  - Green manufacturing
Is *nano* a hype or the future?