Photoconductors

- Bulk photoconductors
  - gain mechanism
  - gain-speed trade-offs
- QWIPs and QDIPs
  - structure, concept, design optimization
  - implementation for enhanced sensitivity
  - multi-color designs

Modulators

- Waveguide structure based modulators
  - Coupler-based
  - Mach-Zehnder based
- Multiple Quantum Well based modulators
  - Concept
  - Alternative designs (surface-normal)
  - Waveguide geometry embodiment
Photoluminescence - light emission from silicon - the latest!!

Several weeks ago when we discussed light emission from semiconductors the question was asked, "Modern silicon wafer boules are extremely pure and have very low defect levels. Shouldn't this silicon show efficient emission?"

We concluded that contrary to popular lore, the photoluminescent efficiency in the bulk of this silicon should be high, but that perhaps non-radiative surface recombination kept the overall efficiency low.

Last Monday experimental data was published* showing this is indeed true:

(Image deleted)


They conclude: "☐ silicon can be a very efficient light emitter if the surface recombination is reduced by efficient surface passivation☐ " and "☐ the EQE of a large number of commercially available float-zone n- and p-type silicon wafers with different resistivities was found to be on the order of a few percent. This shows that our findings are generally valid for highest-quality silicon."

C. G. Fonstad, 5/03  Just 3 days ago!!  Lecture 24 - Slide 2
Photoluminescence - light emission from silicon - cont.

The figures from the article:

Fig. 1: PL external quantum efficiency (EQE) for a 500 µm thick sample at 130 and 297 K. Note the saturation at high excitation levels.

Fig. 2: PL intensity vs. T for four pump levels (15.8, 29.3, 72.9, and 117 mW/cm²). Note the drop at low temperature when phonon population decrease dominates.

Fig. 3: Modulated PL intensity vs. the pump modulation frequency at several temperatures. Note that the response is slow, but also that the speed of a device can be much faster because in a device carriers can be injected and extracted actively, and the minority carrier lifetime need not be the limiting factor.

Photoconductors - single-color QWIP imaging array

(Images deleted)

Photoconductors - two-color QWIP imaging array

(Images deleted)
Modulators - based on waveguide couplers

Applying electric fields to the waveguides changes their effective indices through the electro-optic effect and thus changes the amount of transfer from one guide to the other, making a switch or modulator.

In the lower structure the sign of the field is switched mid-way along the coupler. It can be shown that this results in better control over the switching.

Delta-\(\beta\) coupler

Switched delta-\(\beta\) coupler

See Fig. 11.1 in H.P. Zappe, *Introduction to Semiconductor Integrated Optics*. Artech House, Norwood, MA, 1995.
Modulators - based on Mach-Zehnder interferometer

When a light beam is split, sent through two different paths, and then recombined we create what is known as a Mach-Zehnder interferometer.

If the path lengths are identical, the beams will add constructively and the resulting intensity will be the same as the initial intensity.

If the path lengths differ, the beams will interfere destructively, and the intensity will be reduced accordingly.

The electro-optic effect is used to change effective index in either one leg of the interferometer (above) or in both legs in opposite directions (below).

(Images deleted)

See Fig. 11.10 in H.P. Zappe, *Introduction to Semiconductor Integrated Optics*. Artech House, Norwood, MA, 1995.
Modulators - multi-quantum well structures
Using the quantum-confined Stark effect

(Images deleted)
See Figs. 11.5 and 11.6 in H.P. Zappe, 
*Introduction to Semiconductor Integrated Optics.*

Quantum well band edge profile with and without an applied field, and the corresponding changes in the absorption edge and index.
Modulators - multi-quantum well structures, cont.

Data illustrating the improved characteristics obtained from MQW modulator structures employing multiple coupled quantum well units instead of multiple single (i.e., isolated) wells.

(Image deleted)
See Fig. 5.28 in J. Trezza et al, Heterogeneous Optoelectronics Integration, E. Towe, ed. SPIE Press, Bellingham, WA, 2000.
Modulators - multi-quantum well structures, cont.

A tabulation of some of the many combinations of MQW sections, mirror structures, and operating wavelengths that can be used to achieve various types of devices and modes of operation. Note that the same device can be operated at zero, forward, and reverse bias, and can exhibit a variety of behaviors. For most modulator applications one is concerned only with zero and reverse biases.

See Fig. 5.29 in J. Trezza et al, Heterogeneous Optoelectronics Integration, E. Towe, ed. SPIE Press, Bellingham, WA, 2000.
**Modulators** - multi-quantum well structures, cont.

Multi-quantum well (MQW) modulator operating with light input in the plane of the wells.

MQW modulators are more commonly used with light input normal to the plane of the wells, so this is a useful reminder that in-plane operation is also possible.

(Image deleted)

See Fig. 11.8 in H.P. Zappe, 
*Introduction to Semiconductor Integrated Optics.*