Lecture 24 - Detectors -3; Modulators - Outline

□ 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 questions 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)

See T. Trupke et al, Appl. Phys. Lett. 82 (May 5, 2003) 2996-2998.

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."

Photoluminescence - light emission from silicon - cont.

The figures from the article:

(Images deleted)

See T. Trupke et al, Appl. Phys. Lett. 82 (May 5, 2003) 2996-2998.

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/cm^{-2}). 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)

See Chapter 5 in J. Trezza et al, Heterogeneous Optoectonics Integration, E. Towe, ed.
SPIE Press, Bellingham, WA, 2000.

Photoconductors - two-color QWIP imaging array

(Images deleted)

See Chapter 5 in J. Trezza et al, Heterogeneous Optoectonics Integration, E. Towe, ed.
SPIE Press, Bellingham, WA, 2000.

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-β coupler

(Images deleted)

See FIg. 11.1 in H.P. Zappe, *Introduction to Semiconductor Integrated Optics*. Artech House, Norwood, MA, 1995.

Switched delta-β coupler

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.
Artech House, Norwood, MA, 1995.

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.

(Image deleted)

See Fig. 5.28 in J. Trezza et al, Heterogeneous Optoectonics Integration, E. Towe, ed. SPIE Press, Bellingham, WA, 2000.

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

Modulators - multi-quantum well structures, cont.

A tablulation 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.

(Image deleted)

See Fig. 5.29 in J. Trezza et al, Heterogeneous Optoectonics Integration, E. Towe, ed. SPIE Press, Bellingham, WA, 2000.

Modulators - multi-quantum well structures,cont.

(Image deleted)
See FIg. 11.8 in H.P. Zappe,
Introduction to Semiconductor Integrated Optics.
Artech House, Norwood, MA, 1995.

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.