National Renewable Energy Laboratory
Innovation for Our Energy Future

Modeling Minority-Carrier Lifetime Techniques that use Transient Excess-Carrier Decay

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Why measure minority-carrier lifetime?

Lifetime is reduced when defects are present, so the value of lifetime can give an estimate of material quality.

Transient techniques for measuring minority-carrier lifetime in silicon

- Microwave Reflection Photoconductive Decay (μ-PCD)
- Resonant-Coupled Photoconductive Decay (RCPCD)
- Transient Free-Carrier Absorption (FCA)

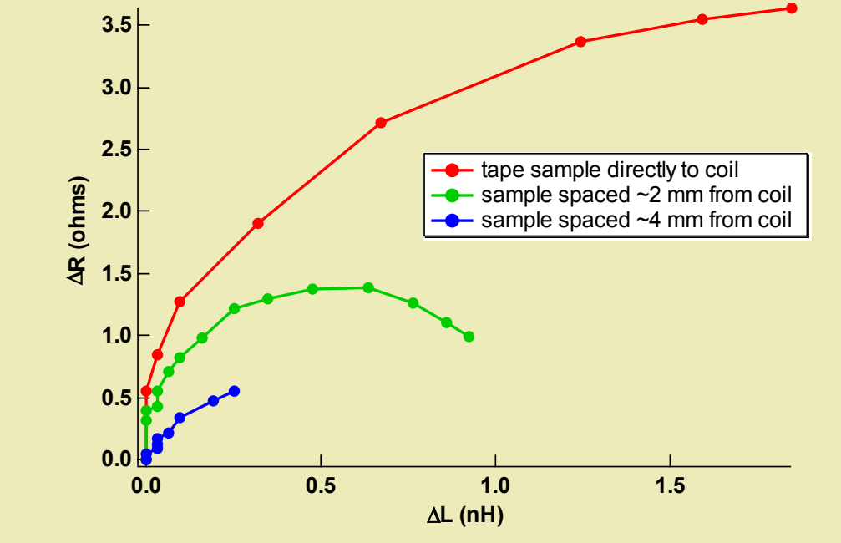
These techniques are
- Contactless
- Indirect and small bandgap materials can be measured
- Transient technique gives direct measure of decay rate

How do μ-PCD and RCPCD work?
- Excess carriers are created by light pulses and increase the conductivity of the sample.
- Small antenna or open-ended waveguide senses changing photoconductivity in the sample.
- Electronic circuitry measures the decay of photoconductivity as carriers in the sample recombine to equilibrium concentration.

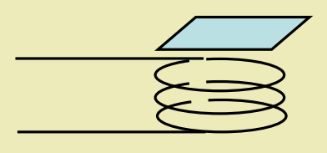
Resonant-Coupled Photoconductive Decay (RCPCD)

Couple sample to coil

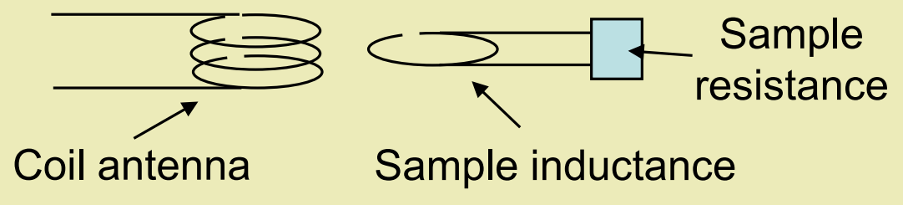
Experimentally-measured impedance with increasing light on sample



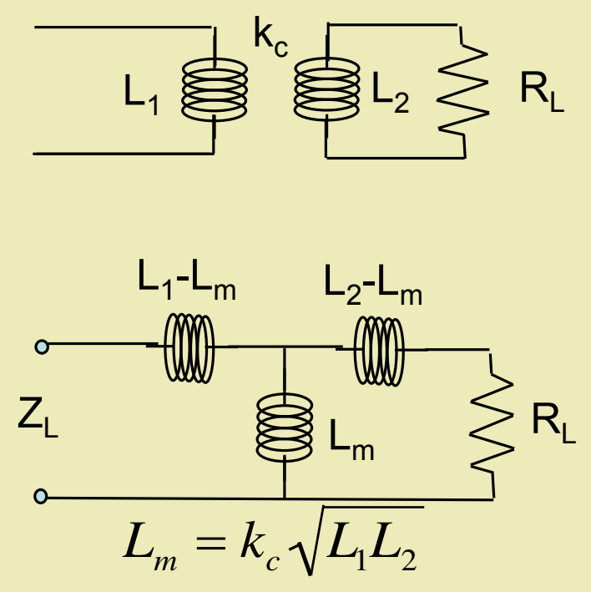
Model coil and sample



Coupled inductors (like transformer) and sample as 1-turn coil

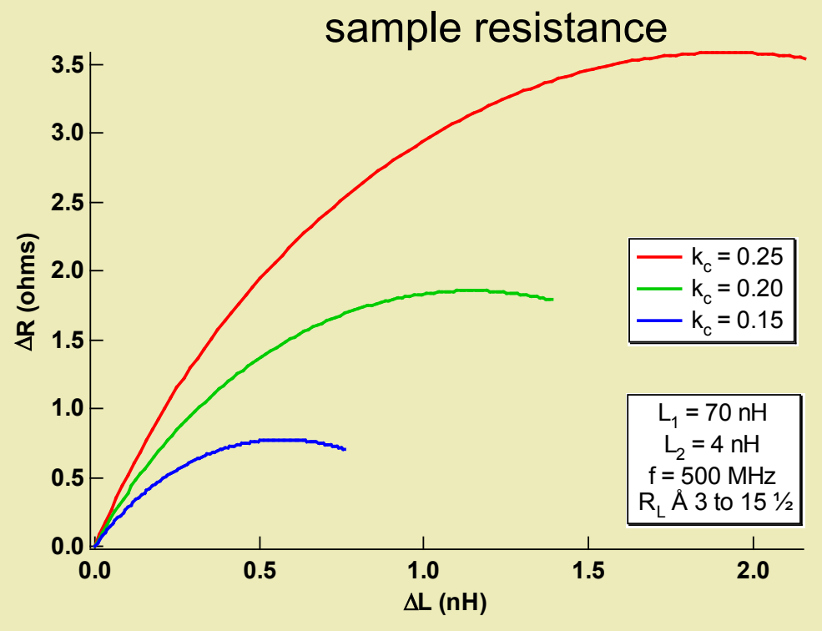


Circuit models

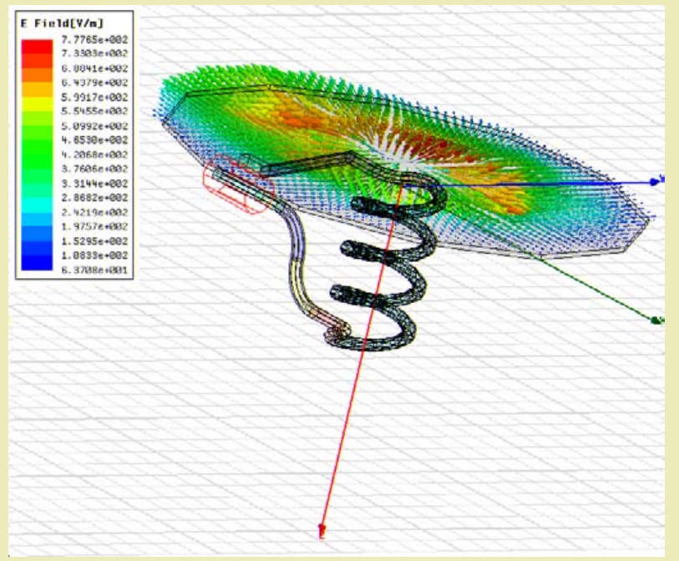


$$L_m = k_c\sqrt{L_1 L_2}$$

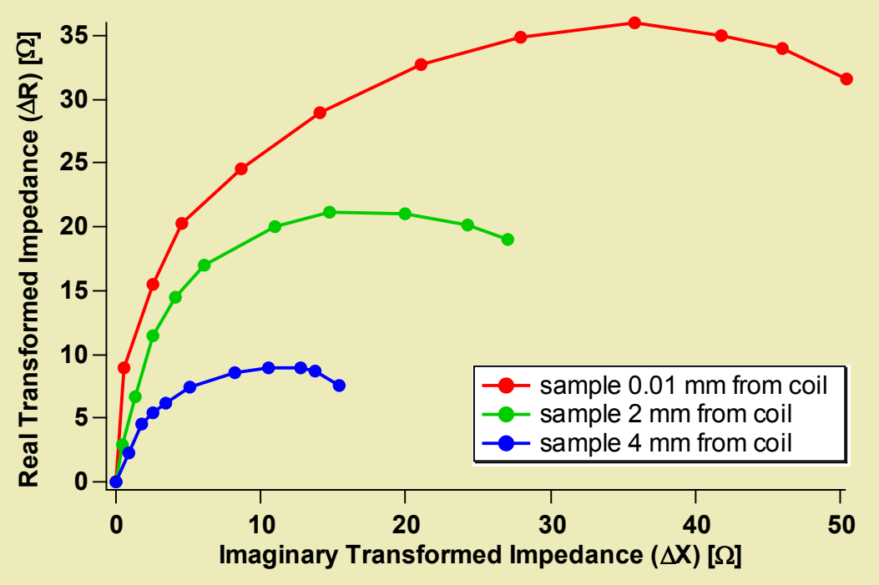
Circuit-modeled impedance with changing sample resistance

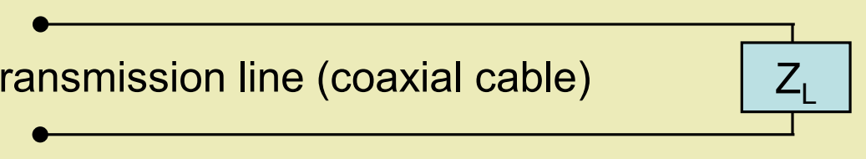


Ansoft HFSS Modeling



HFSS-modeled impedance with changing sample conductivity



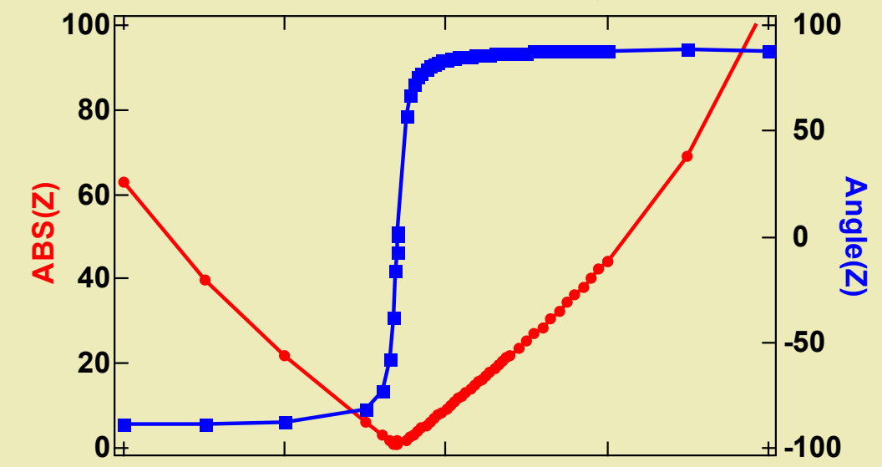


Add transmission line (coaxial cable)

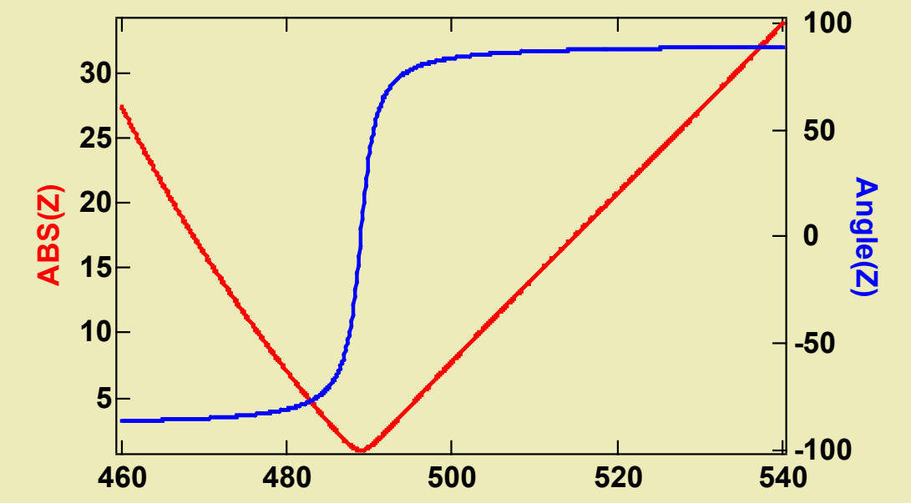
$$Z_{trans} = Z_O \frac{Z_L - iZ_O \tan(\beta z)}{Z_O - iZ_L \tan(\beta z)}$$ where

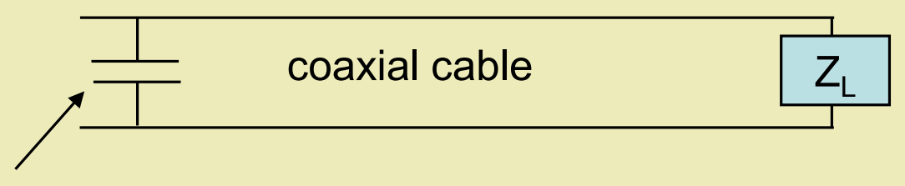
$\beta = 2\pi/\lambda$
z = length of coax
Z_O = 50 Ω characteristic impedance

Measured impedance analyzer data



Modeled coil on transmission line



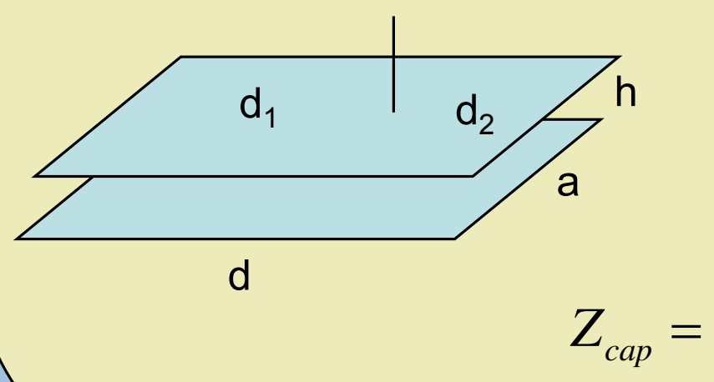


Add capacitor

Model capacitor: $$S(\omega) = \omega C\left(\frac{\frac{2}{\omega\tau}\sin(\omega\tau)}{[\cos(\omega\tau)+\cos(\xi\omega\tau)]}\right)$$

where: $C = \frac{\varepsilon_o a d}{h}$

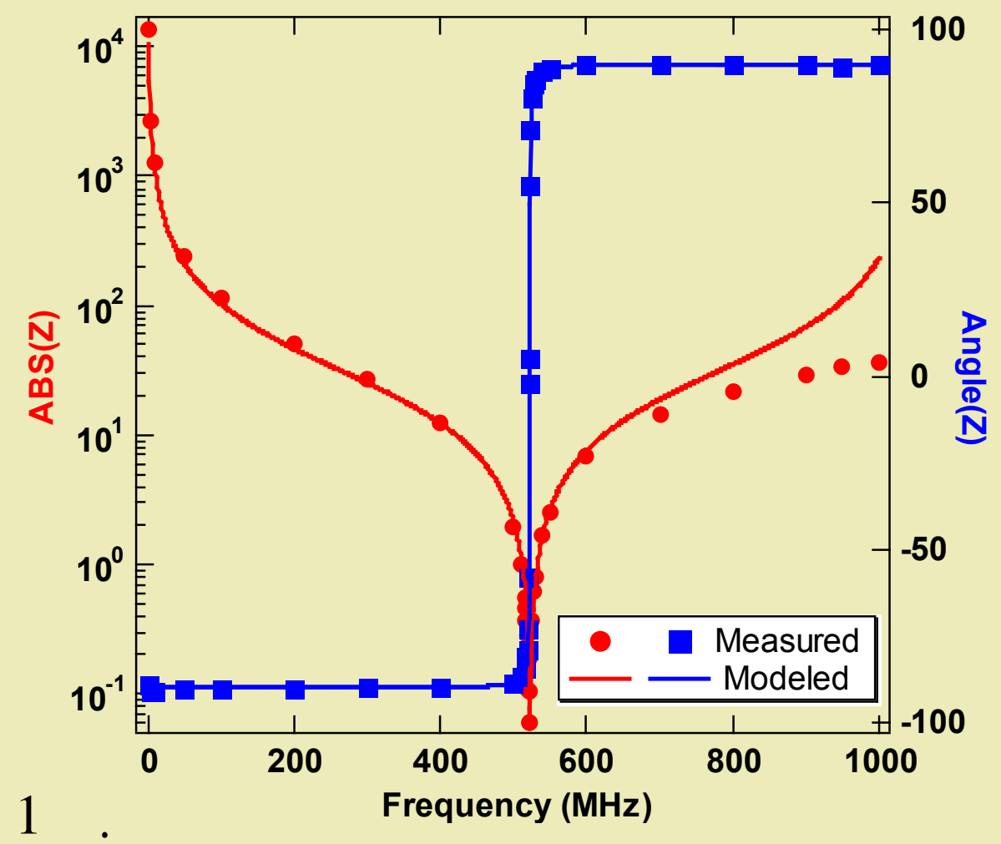
$\tau = \frac{d}{v_o}$ and $\xi = \frac{d_2 - d_1}{d}$



$$Z_{cap} = 0.05 - \frac{1}{S(\omega)}i$$

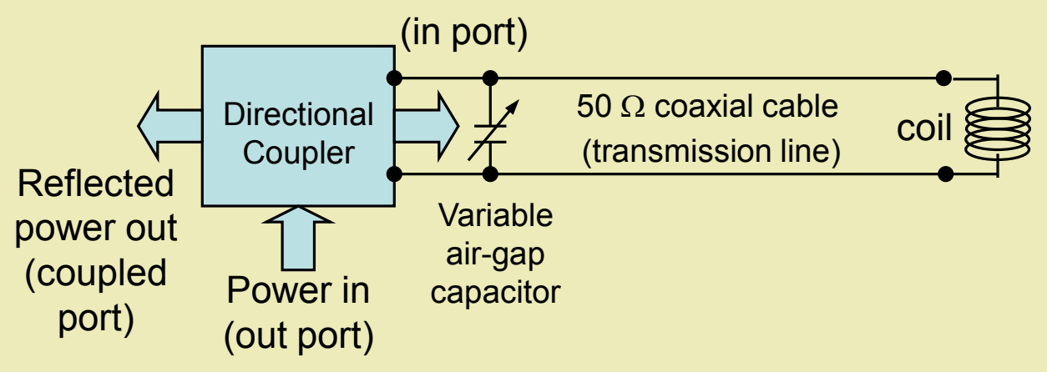
Best fit real resistance

Measured and modeled values for a variable air-gap capacitor set at ~15 pF

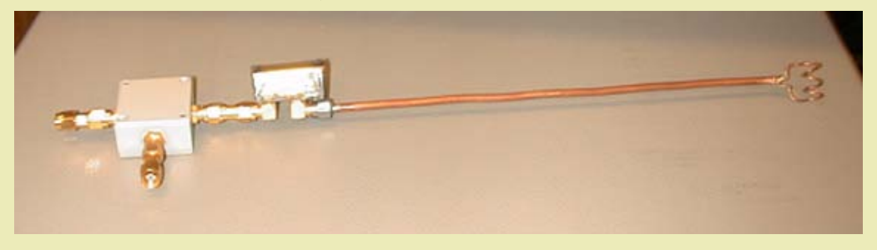


"Capacitor Modeling at High Frequencies" J.A.B. Faria, IEEE Trans. on Education **35**, 1992, pp. 214-216.

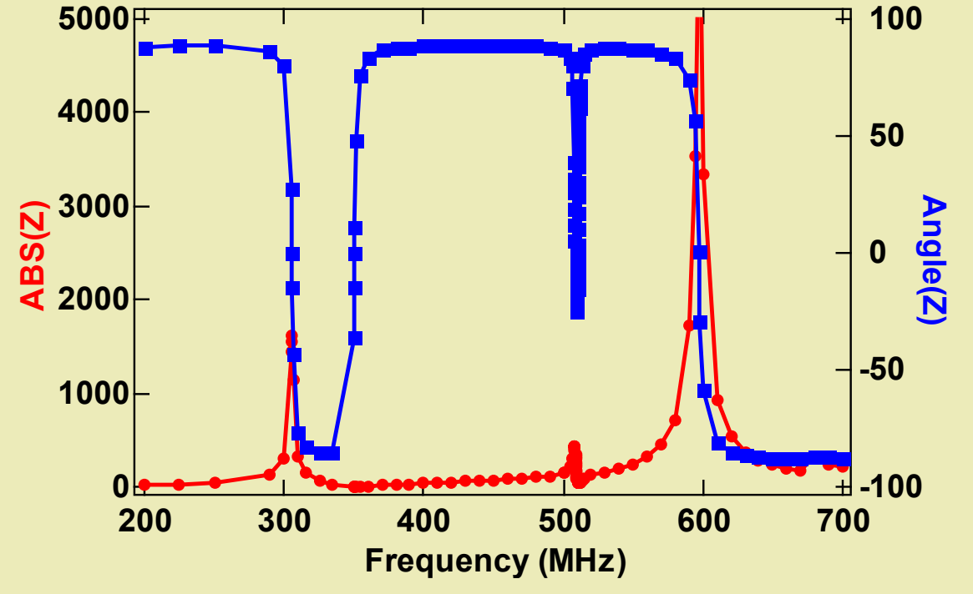
Use directional coupler, or circulator, to send power to antenna and monitor reflected power due to sample photoconductivity



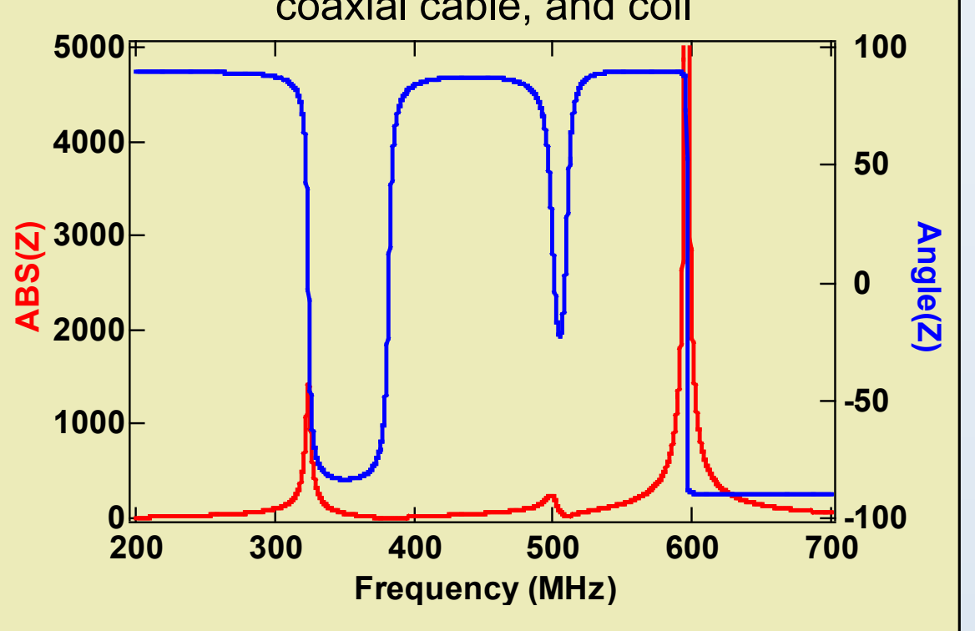
Circuit photo showing directional coupler, shielded tunable capacitor, semi-rigid coaxial cable, and coil antenna



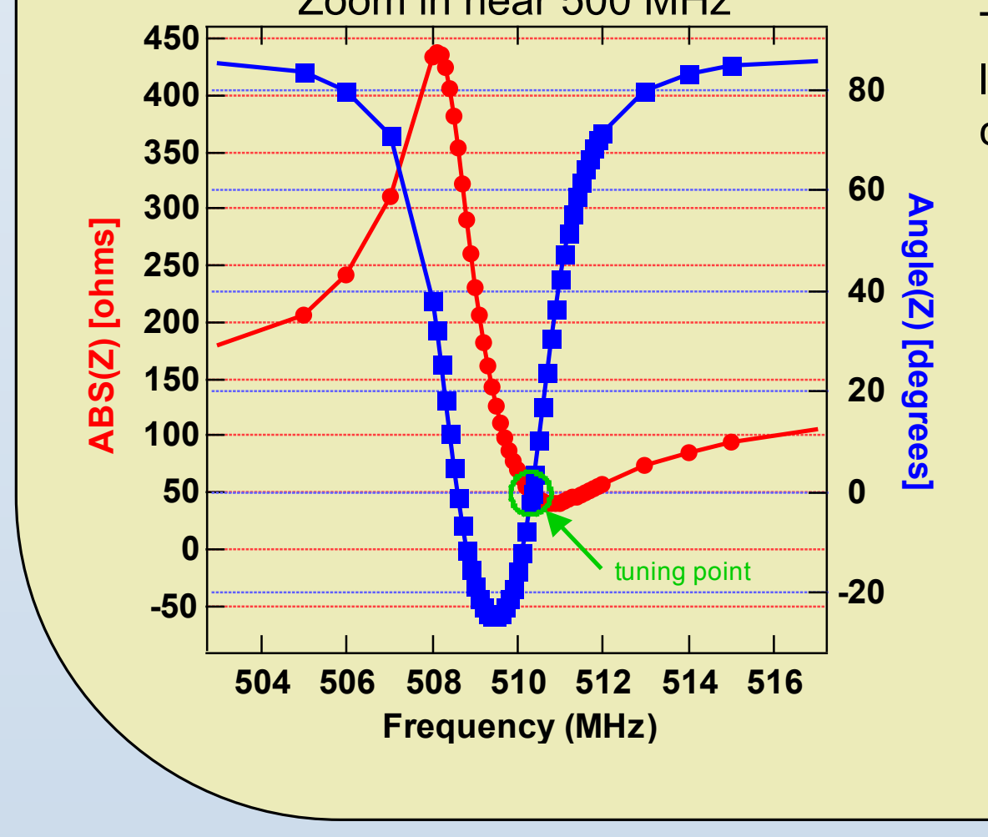
Measured impedance analyzer data of capacitor, coaxial cable, and coil



Modeled circuit of capacitor, coaxial cable, and coil



Zoom in near 500 MHz

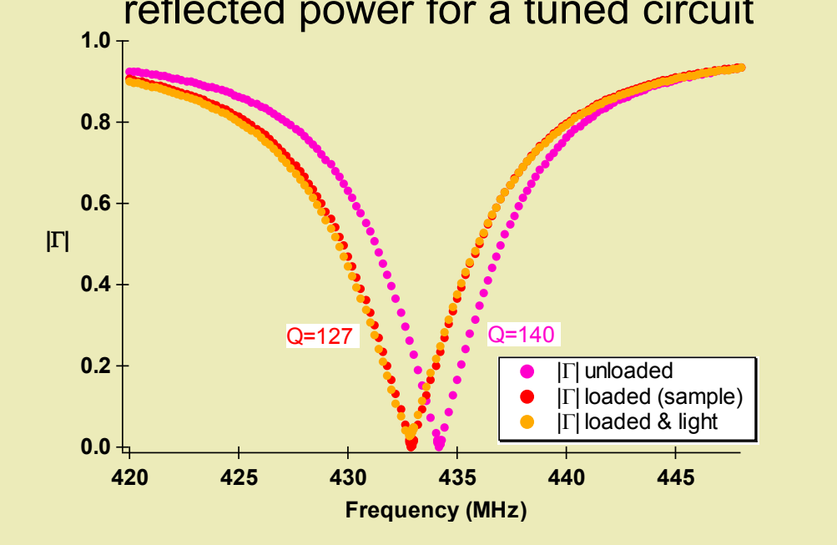


The combination of coil impedance, coaxial cable length, and capacitance resonance leads to a circuit impedance resonance near 500 MHz.

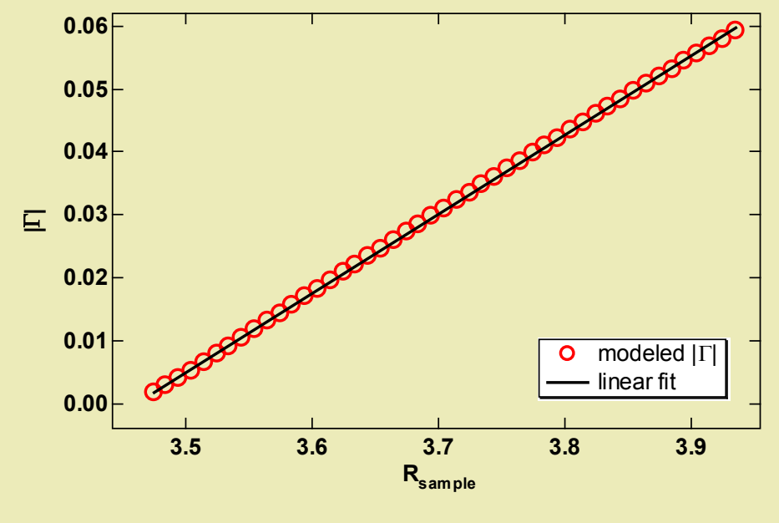
At the tuning point, the impedance magnitude is 50 Ω, and the impedance angle is 0°. For this condition there is no reflected power from the directional coupler, Γ = 0.

While samples vary in size, shape, and conductivity, the tuning point can be found by adjusting the capacitor, frequency, and the coupling distance of the sample to the coil antenna.

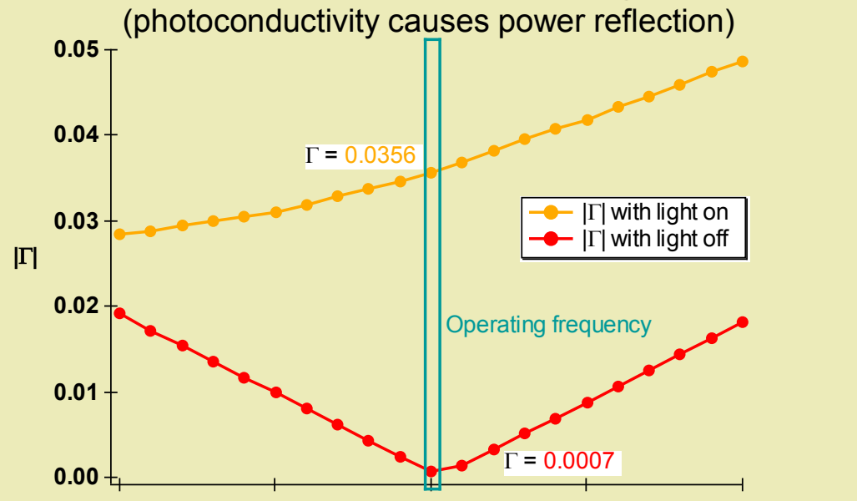
Measured frequency response of reflected power for a tuned circuit



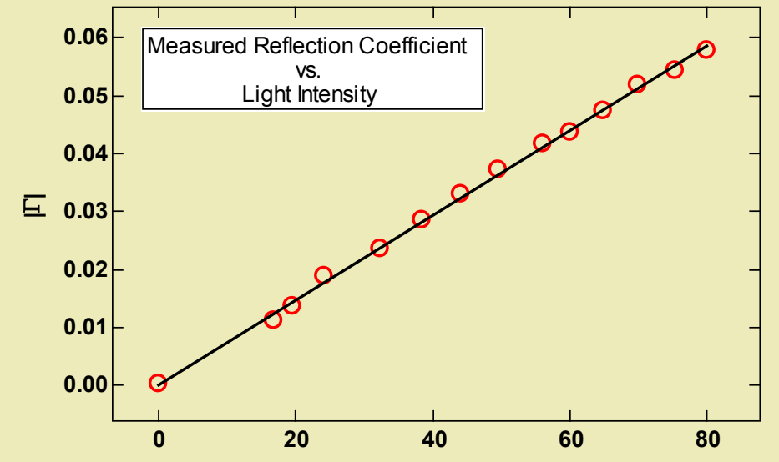
Modeled response of power reflection due to sample resistance



Expanded view of operating point
(photoconductivity causes power reflection)



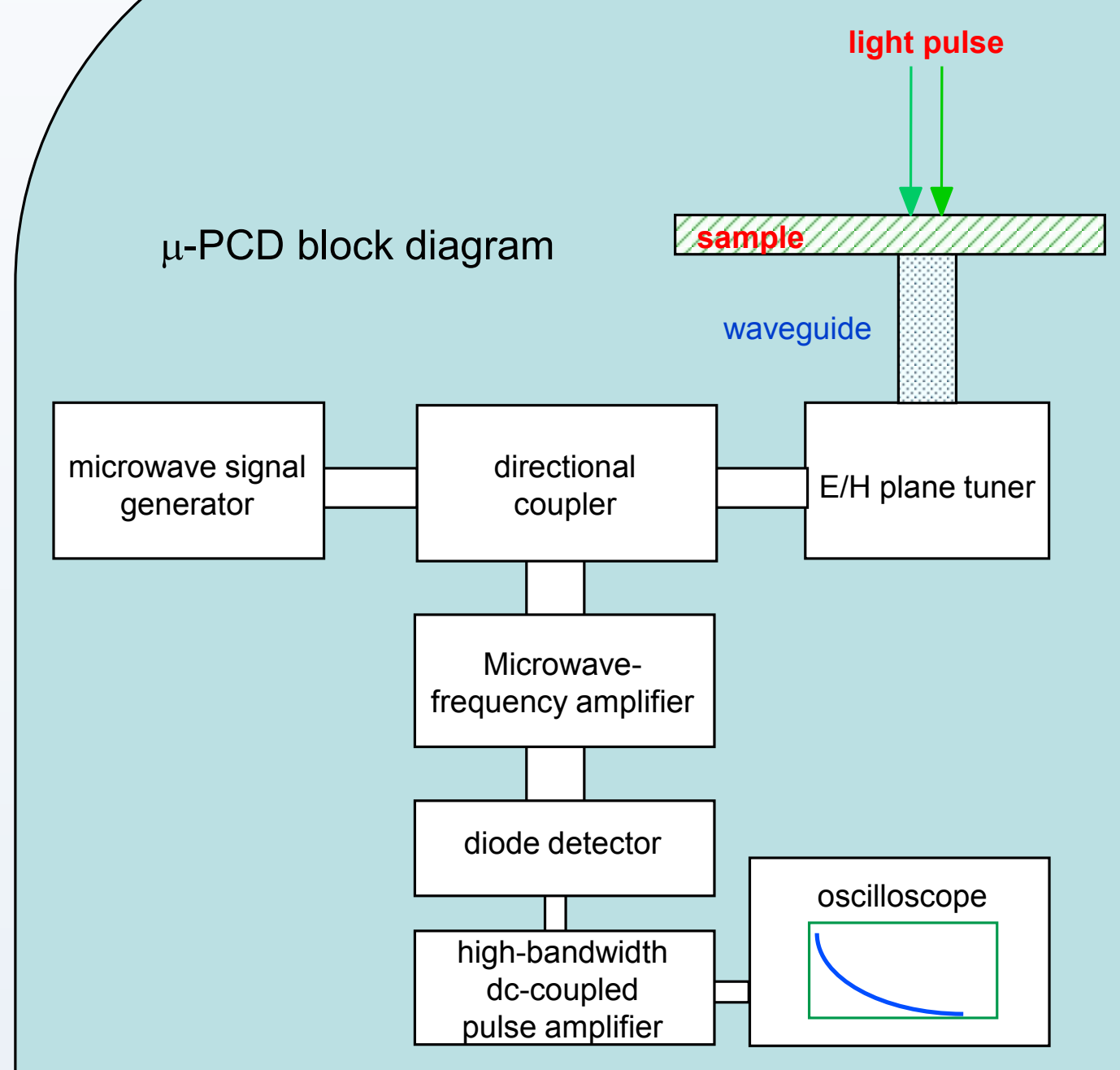
Measured power reflection coefficient due to sample photoconductivity



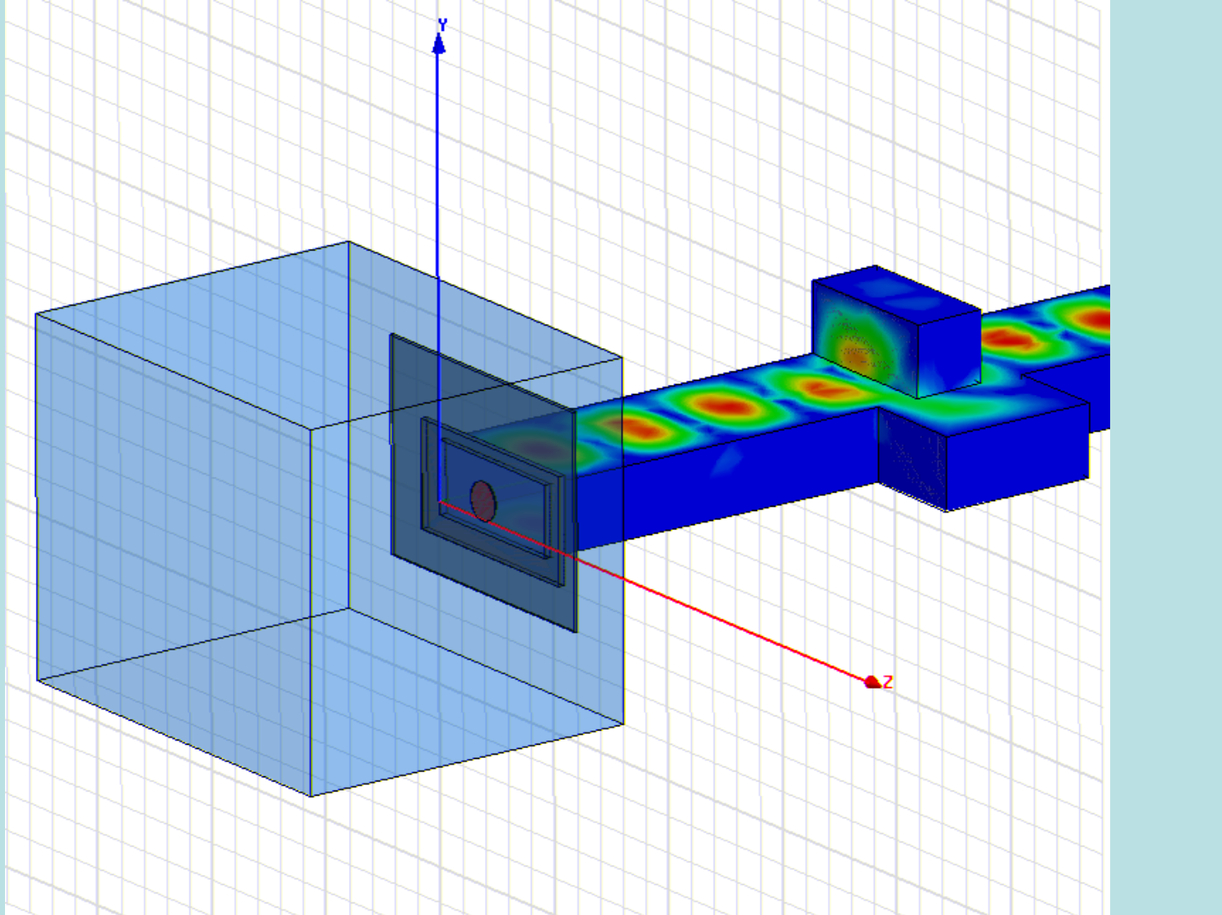
(pulse amplifier saturates when Γ~0.05, so measurements are made for 0<Γ<0.05)

Microwave Reflection Photoconductive Decay (μ–PCD)

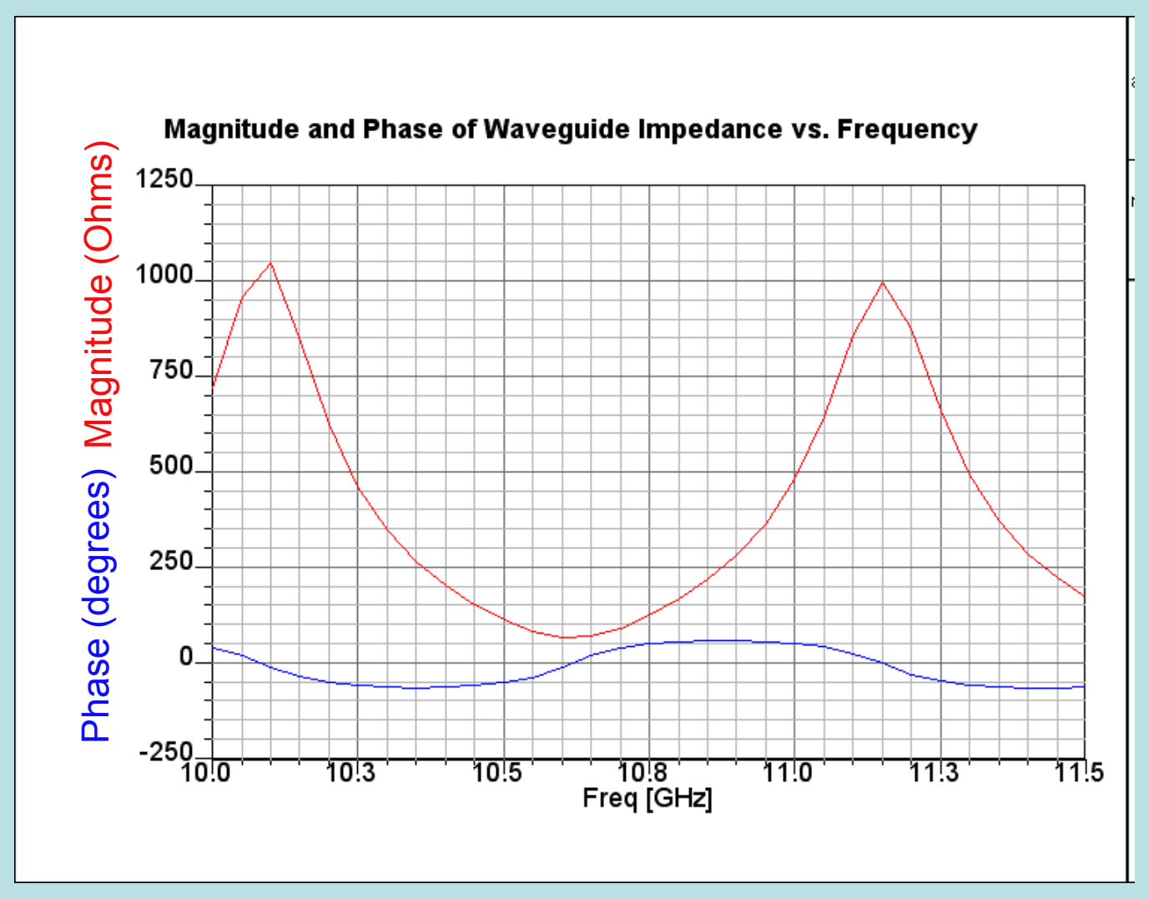
μ-PCD block diagram



Simulated waveguide structure for μ-PCD Using Ansoft's HFSS software

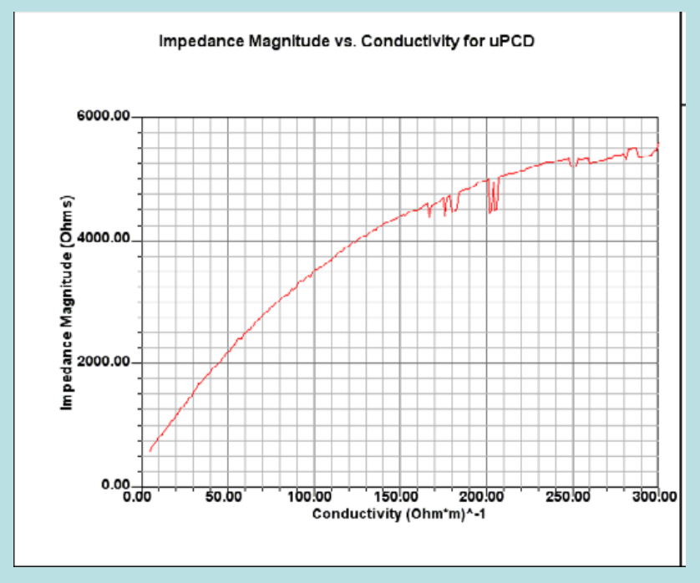


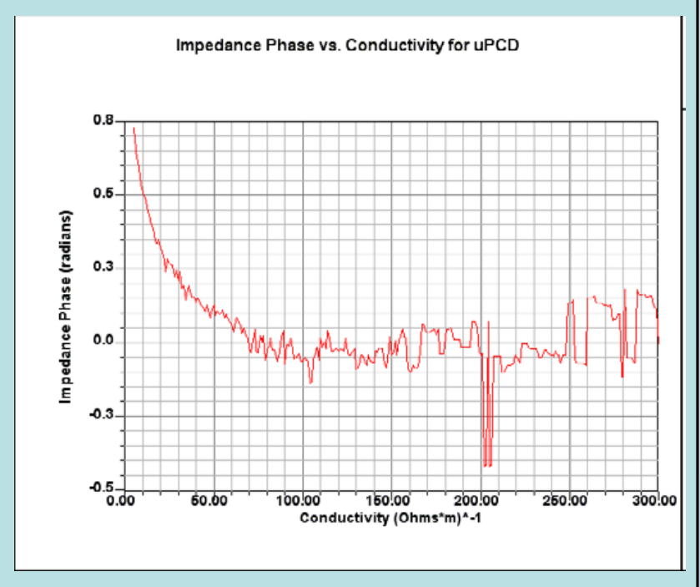
The large box represents air for calculation purposes. The gray square is a semiconductor sample. The red spot represents the laser spot where conductivity is changed. The blue waveguide includes E and H plane tuning stubs and has the ☐E-field magnitude superimposed on it.



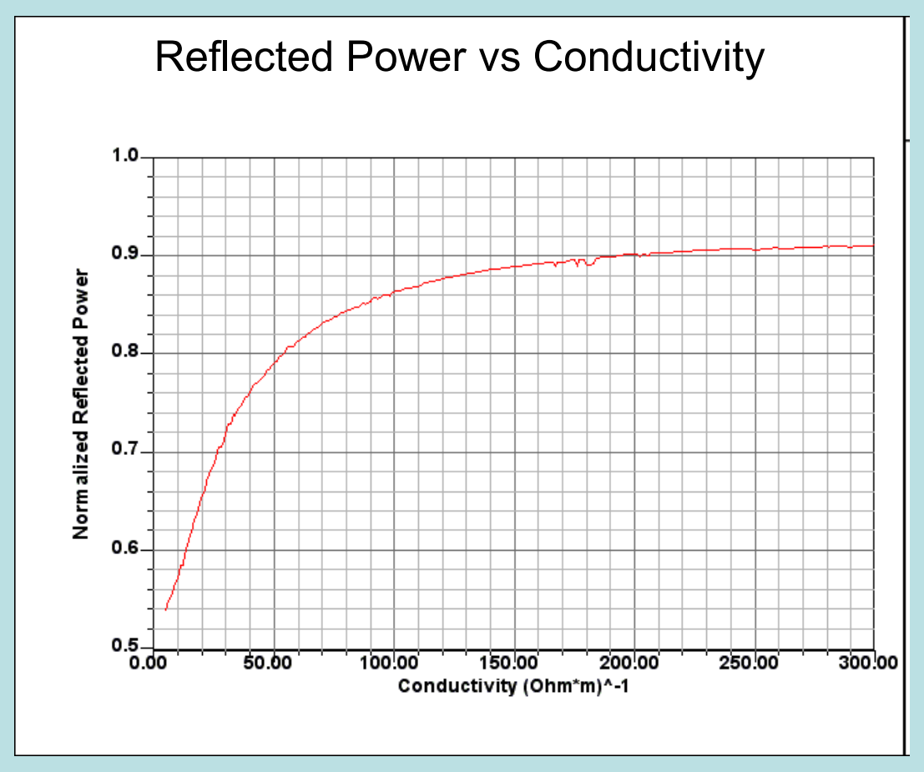
Tuning of the waveguide is accomplished using the E and H plane stubs and by adjusting frequency. Tuning to a zero point in phase with a magnitude minimum results in a linear phase response to changing conductivity, but magnitude response is noisy. Tuning to a magnitude maximum results in good magnitude response but phase is noisy. Therefore, best linearity results from tuning to a frequency between the minimum and maximum values of the waveguide impedance magnitude.

The graphs below show the magnitude and phase of the waveguide's impedance as the conductivity in the spot of the wafer is changed. The magnitude shows a large linear range; however, the phase approaches a minimum. This leads to a noisy, poorly-resolved solution, and as can be seen below, the reflected power also becomes non-linear.





Reflected Power vs Conductivity



HFSS is used to simulate reflected power, the quantity that is actually measured experimentally. As can be seen, there is a region of linearity at low injection levels. But, as the spot's conductivity increases into high injection, the curve levels off, thus limiting the range of this method to lower injection levels. It is worth noting, though, that the linear region covers over 10% of possible reflected power, resulting in a strong, clean signal.

Transient Free-Carrier Absorption (FCA)

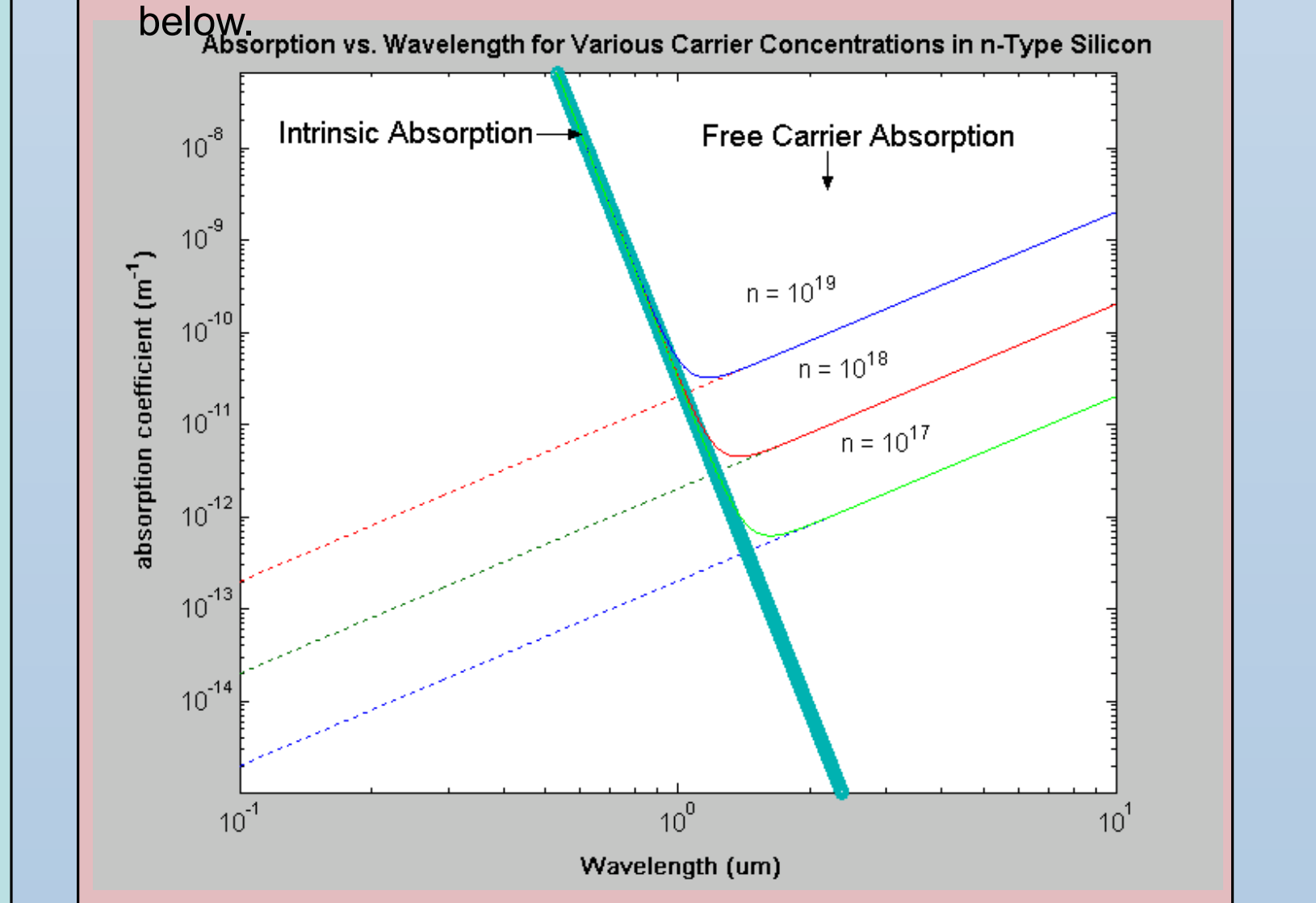
Free carrier absorption in semiconductors is given by

$$\alpha = \frac{q^3\lambda^2 p}{4\pi^2\varepsilon_o c^3 n m^{*2}\mu}$$, where

λ = wavelength
p = density of free carriers
n = refractive index
m* = effective mass, and
μ = mobility.

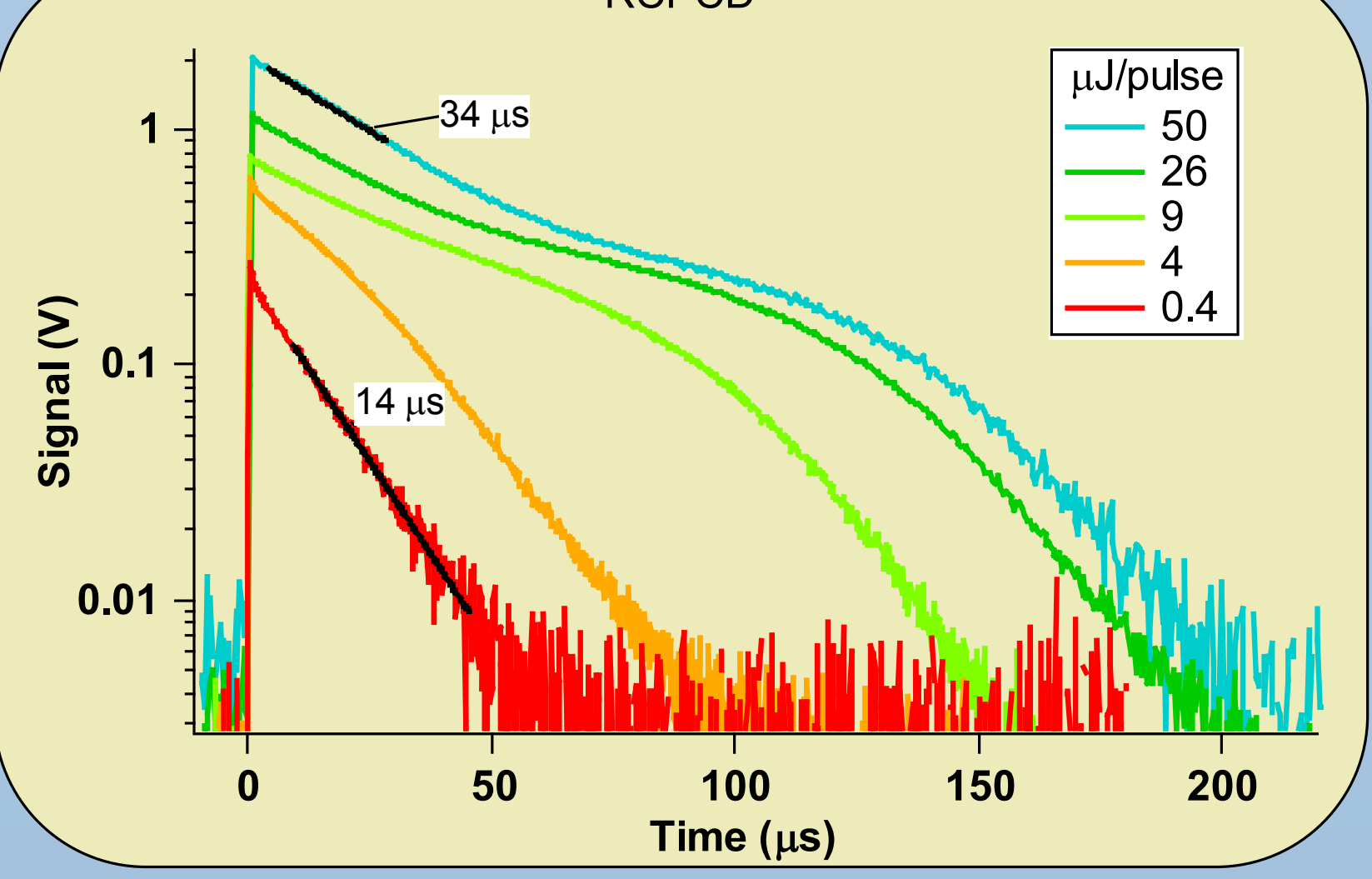
D. K. Schroder et al., "Free Carrier Absorption in Silicon", IEEE J. Solid-State Circuits **SC-13**, 1978.

Free carrier absorption is a linear function of the density of free carriers. Light with an energy greater than that of the bandgap is intrinsically absorbed. This is displayed in the left portion of the graph below. For light with wavelengths longer those corresponding to the bandgap energy, the absorption coefficient is linearly proportional to the carrier density. This infrared absorption is displayed on the right portion of the graph below.

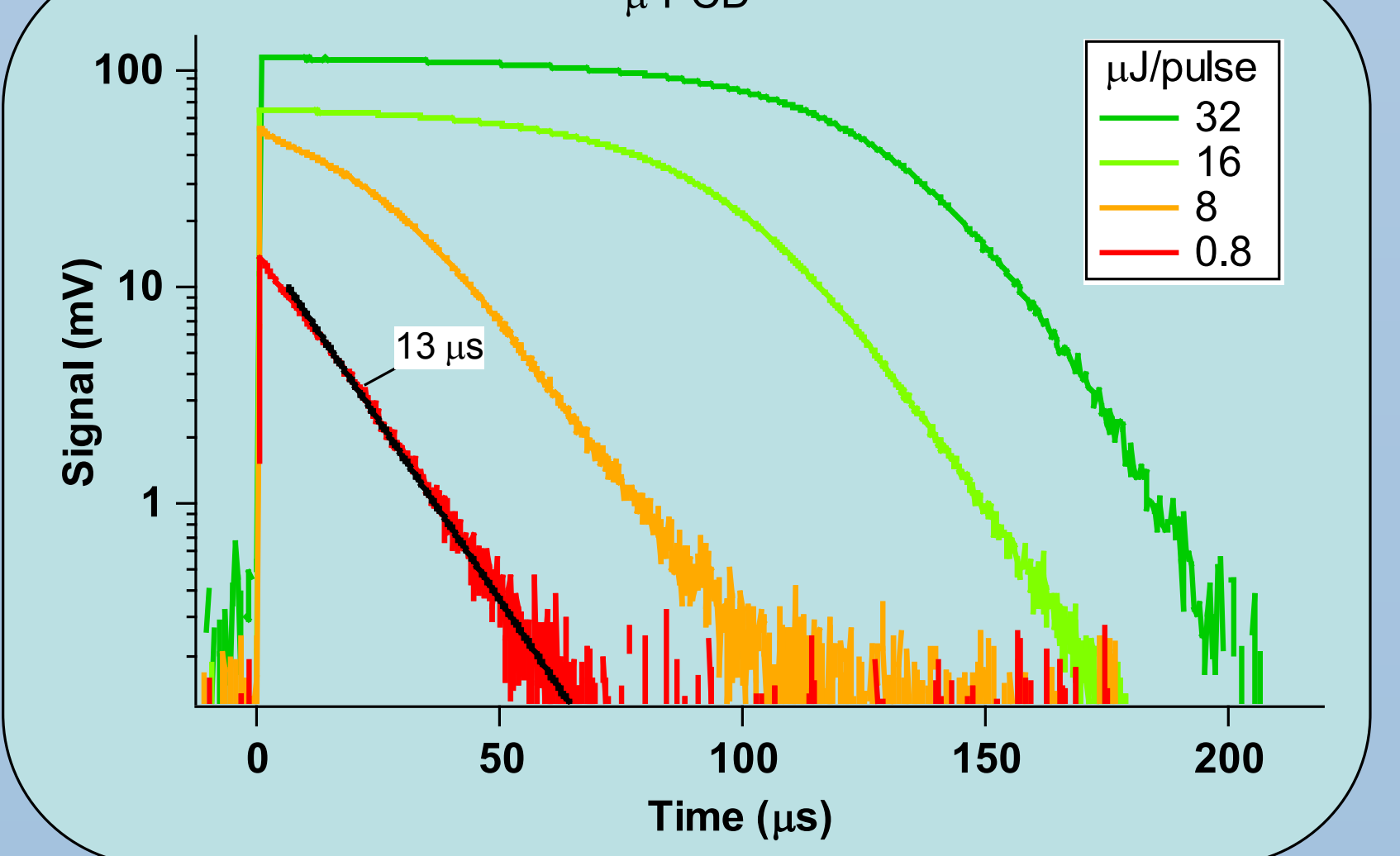


Unpolished surfaces scatter light and reduce the infrared beam's transmission. We have measured a double-polished wafer, yet the signal is still small compared to background noise and requires higher injection levels than μ-PCD and RCPCD.

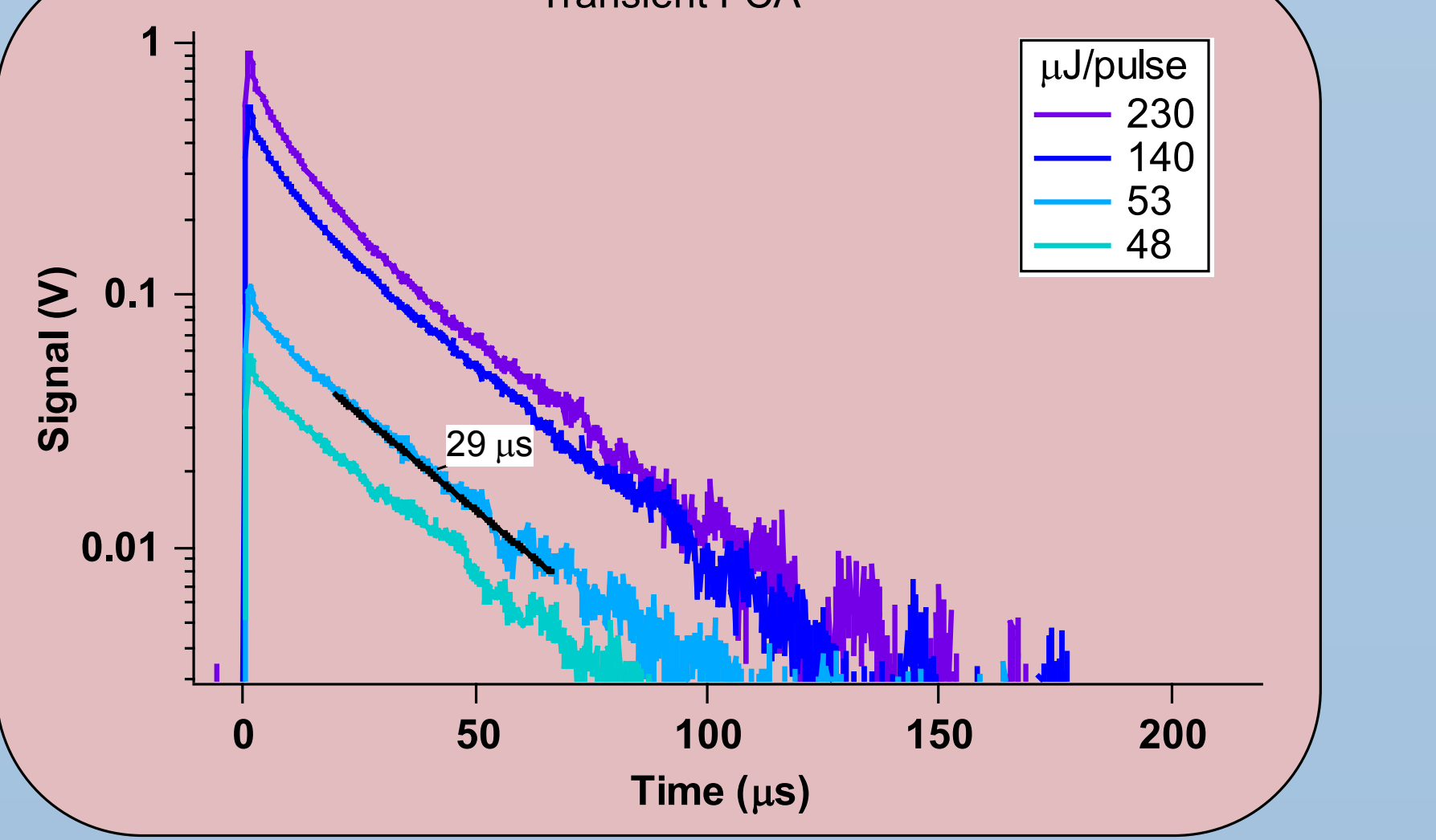
RCPCD



μ-PCD



Transient FCA



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