Terahertz Time-Domain Spectroscopy for Characterization of Doping Profiles in Semiconductors

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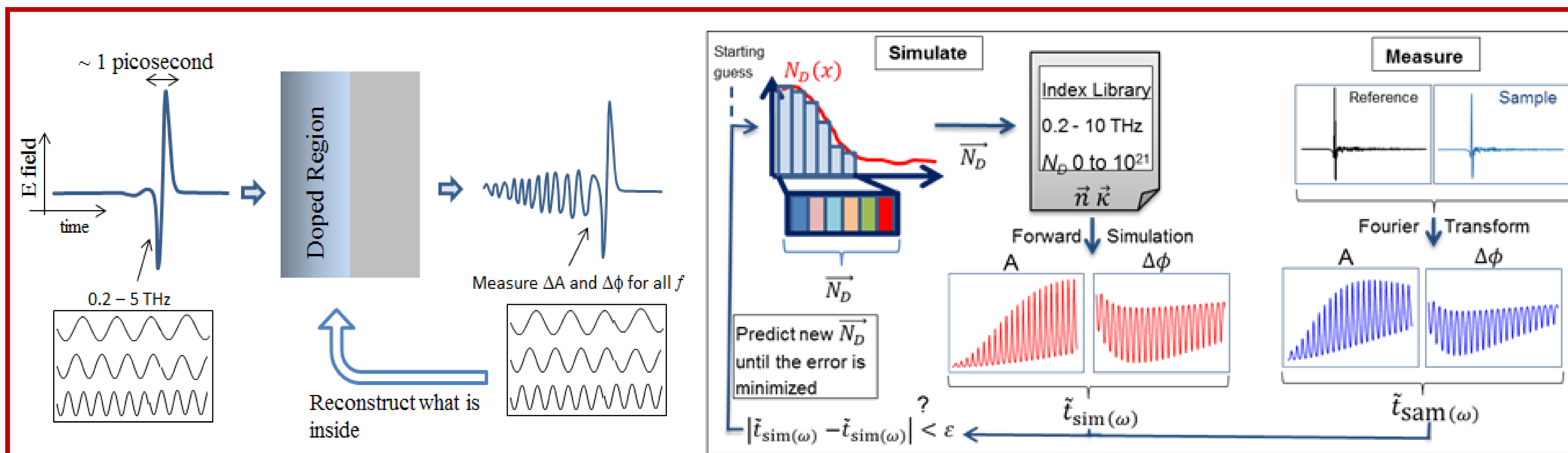
Introduction

Rapid progress in ultrafast fiber laser technology has enabled the emergence of several robust commercial terahertz metrology systems suitable for use in a manufacturing environment. Terahertz time-domain spectroscopy (THz-TDS) can accurately and rapidly measure the attenuation and phase delay for every frequency in the pulse bandwidth of the terahertz pulses generated and detected (by taking the Fourier transform). Here, we have extended the use of THz to monitor continuously varying depth profiles . Phosphorus doped profiles in p type silicon wafers have been investigated to reconstruct doping profiles from terahertz transmission using THz-TDS. The results demonstrate the use of this technique for rapid, non-destructive determination of diffusion profiles with a potential for in situ profile monitoring.

Principle

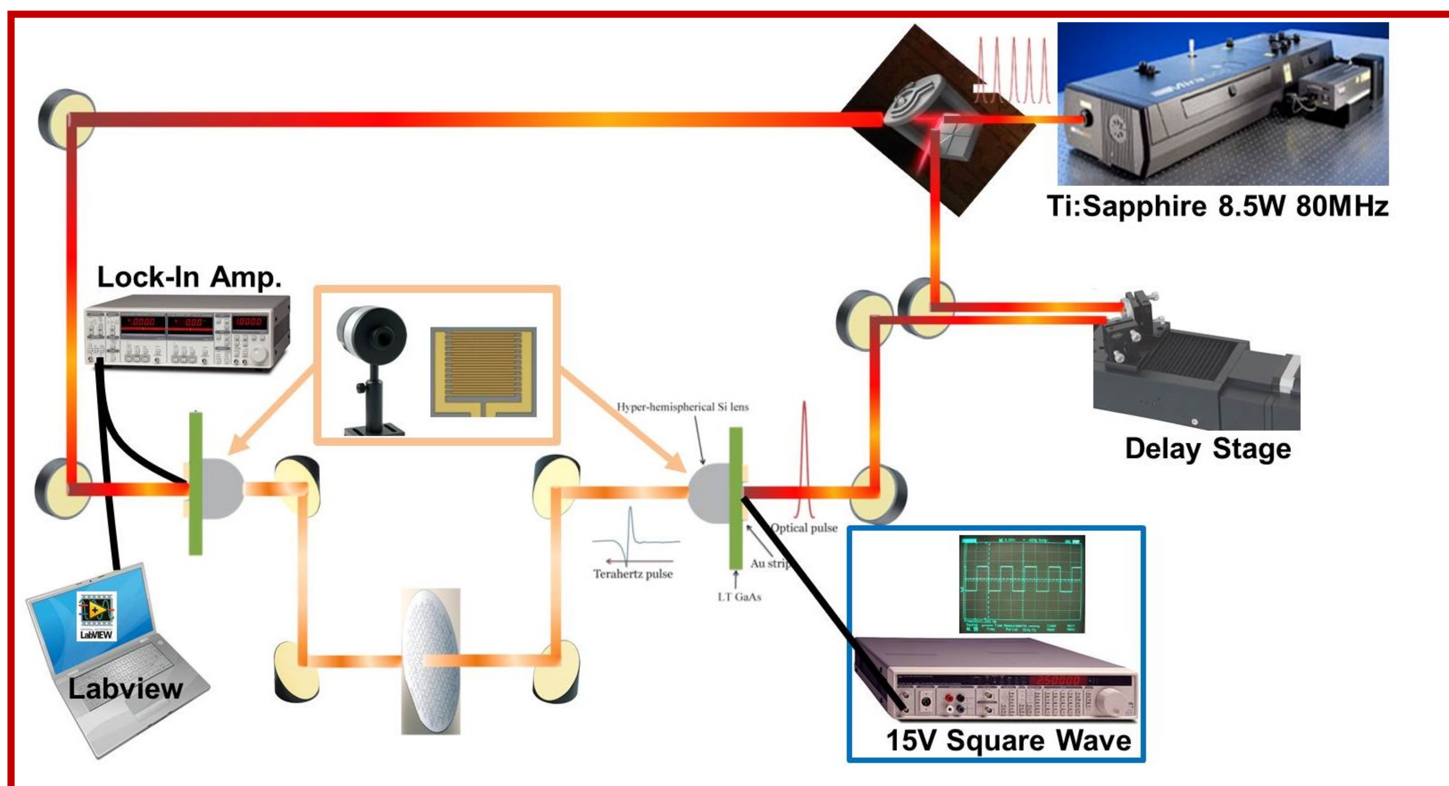
- Suitable photon energy makes THz an unambiguous optical probe of free carrier properties.
- THz-TDS can accurately measure the attenuation and phase delay for every frequency in the pulse bandwidth.
- The difference of complex THz transmission between the measurement and simulation from the transfer matrix is utilized to map an electrical doping profile.



Schematic of the algorithm that solves the inverse problem of mapping unknown doping profiles. The algorithm inputs are measured amplitude and phase data and it also needs a real and imaginary index library.

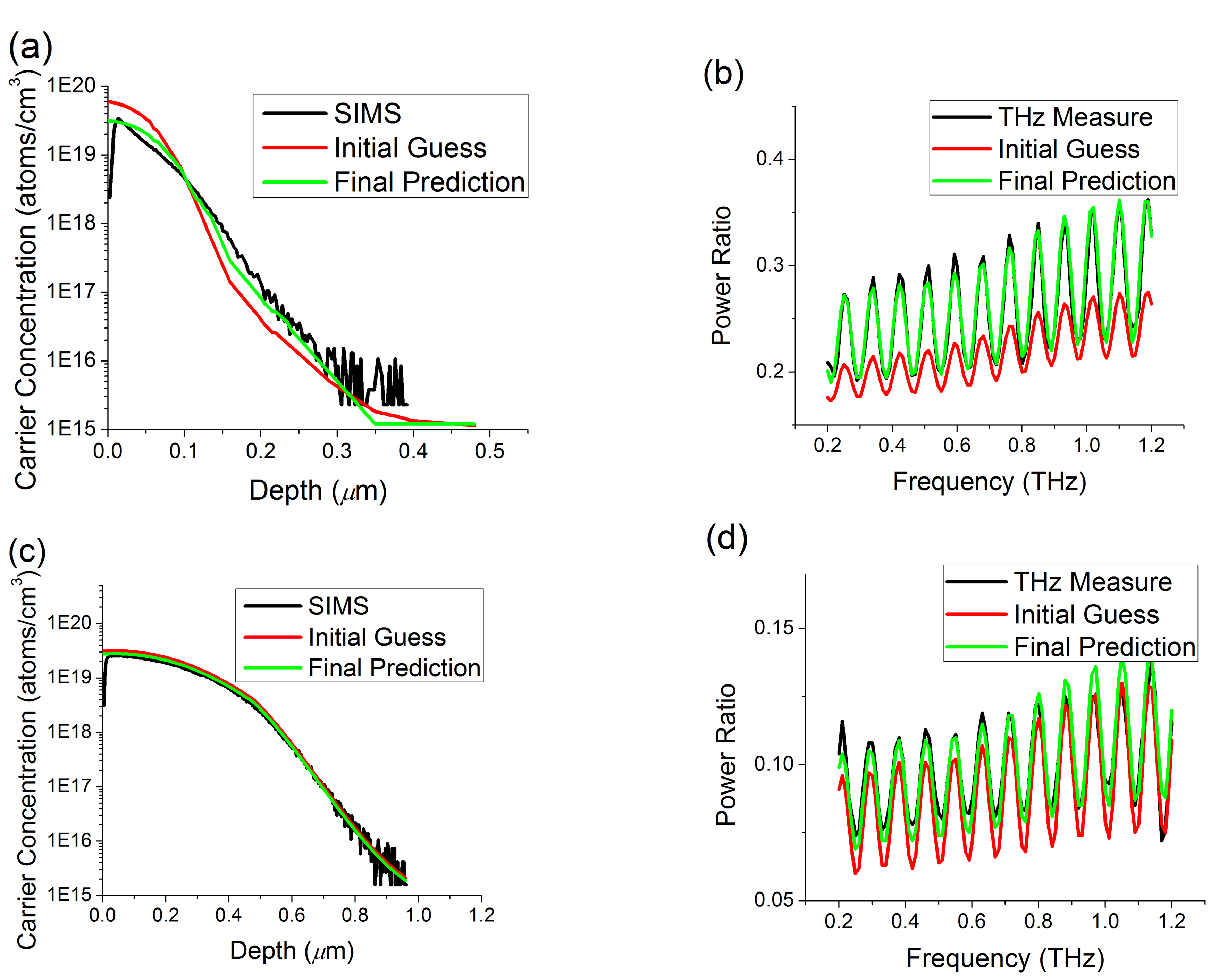
Set Up

- **A Ti:Sapphire laser generated pulse train is utilized to photo-excite carriers in two identical Photoconductive antennae (PCA).**
- **PCAs generate and detect free-space broadband terahertz pluses.**
- **A moving mirror controls the arrival of THz pluses.**
- **The signal from the detector PCA's is amplified directly through a lock-in amplifier to map out terahertz pulses on a sub-picosecond timescale.**



Terahertz pulses containing multiple THz frequencies are generated from ultra-short (~ 150-200 fs) red (830 nm) laser pulses.

Results



Demonstration of doping profile prediction with initial guess profiles from TCAD and its comparison with the SIMS measurements for (a,b) ion implanted, rapid thermally annealed with a dose of $1x10^{15}$ cm^{-2}; (c,d) thermally diffused with a dose of $2x10^{15}$ cm^{-2}.

Conclusions/Benchmarks

Techniques	Non-contact	Non-destructive	Speed	Cost	Chemical profile	Active doping profile
SIMS	No	No	Slow	High	Yes	No
CV	No	Sometimes	Fast	Low	No	Maybe
ECV or SRP	No	No	Slow	Medium	No	Yes
nc-CV	Yes	Yes	Fast	Medium	No	No
Ellipsometry	Yes	Yes	Moderate	Medium	No	No
THz	Yes	Yes	Fast	Medium	No	Yes

Capabilities	Limitations
Can penetrate through most materials and hence measure buried features and multilayer samples. Scattering due to intentional or natural surface roughness or scuff is almost never an issue due to the large wavelength of THz light (~ 1 mm)	Cannot penetrate metal layers. Cannot penetrate thick layers of most liquids (e.g. water). The practical THz beam diffraction limit of ~ 0.5mm means a minimum spot size of about 1 mm which limits lateral resolution.
Measurement Speed: Fast - seconds for compliance checking and minutes for full mapping.	Cost: Significantly lower than alternatives in table above.
Profiling Resolution: To determine and improve the profiling resolution is a key aim for future studies. Projected resolution appears comparable to SIMS: ~ 10 nm at higher doping.	Very sharp doping profiles (≤ 10 nm) like delta doping cannot be profile mapped. However, overall dosage, dopant activation and failure of delta doping can be measured in delta doped junctions.

Applications in Semiconductor Manufacturing
Quick Determination of Dopant Profiles on Monitor Wafers
In Situ Monitoring of Post Rapid Thermal Annealed Dopant Activation