ENZ Al-Doped ZnO for Ultrafast Switching at Telecom:
Outpacing the Amplitude-Bandwidth Trade-Off

PURDUE UNIVERSITY Discovery Park

N. Kinsey, C. DeVault, J. Kim, M. Ferrera, V.M. Shalaev, A. Boltasseva
Electrical and Computer Engineering, Birck Nanotechnology Center, Purdue University West Lafayette IN, 47907

Introduction

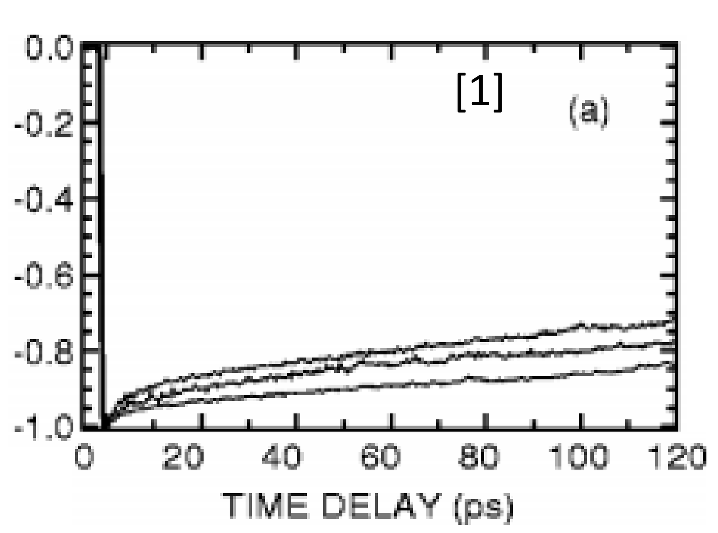
Transparent conducting oxides (TCOs) are promising CMOS-compatible materials due to their unique optical properties, ability to achieve plasmonic properties at telecom, and dynamic tunability. However, the slow electron-hole recombination time limits the speed at which optical modulation can occur. Here, we report the optical tunability of a unique oxygen-deprived aluminum doped zinc oxide (AZO) film where 40% modulation is achieved in reflection with a total recovery speed less than 1 ps. Through modeling of the physics, critical parameters such as the carrier density and change in refractive index are extracted which will aid the development of future all-optical devices. The extracted parameters were also used to design an integrated all-optical plasmonic modulator achieving 0.4 dB/µm extinction with an insertion loss of <0.1 dB/µm.

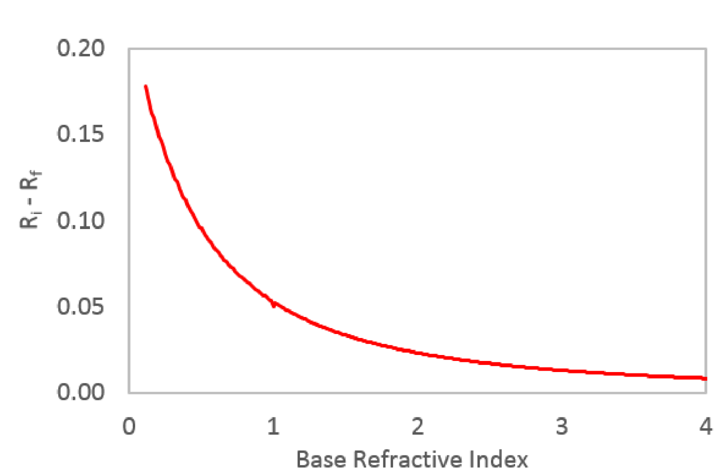
Speed vs Amplitude

Optical modification of the carrier density offers the potential for an ultrafast method of tunability. However, many of the traditional materials such as silicon and gallium arsenide have a slow electron-hole recombination time (>100 ps for silicon [1]). By growing low-temperature structures which include high levels of defects, this was overcome [2]. Unfortunately, the signal strength is quite poor, ~1% for LT-GaAs, abiding by the amplitude-bandwidth trade-off. However, this too can be overcome by altering the intrinsic optical properties of the medium. Low refractive index materials (i.e. ENZ) provide a larger absolute change in the reflection when compared to high index materials. Thus, the optical response can be maximized in the ENZ regime.

In summary we want our material to have the following properties:

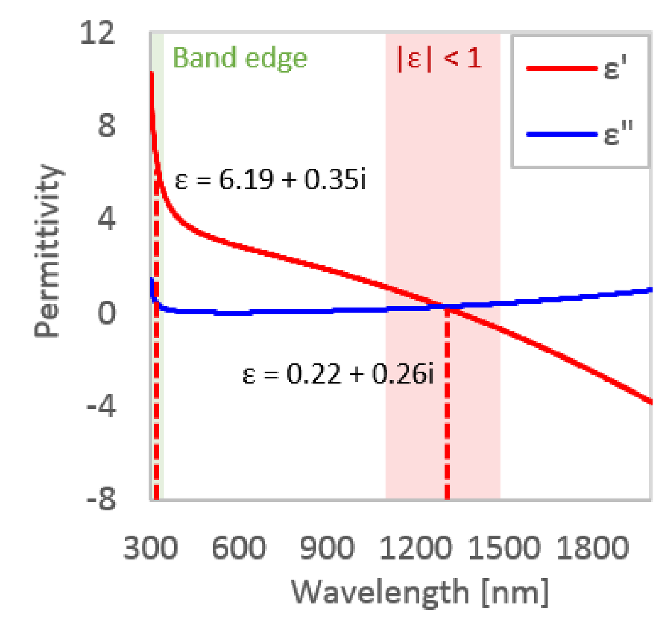
1) Fast electron-hole recombination time
2) Low refractive index
3) CMOS-compatible
4) Established fabrication techniques

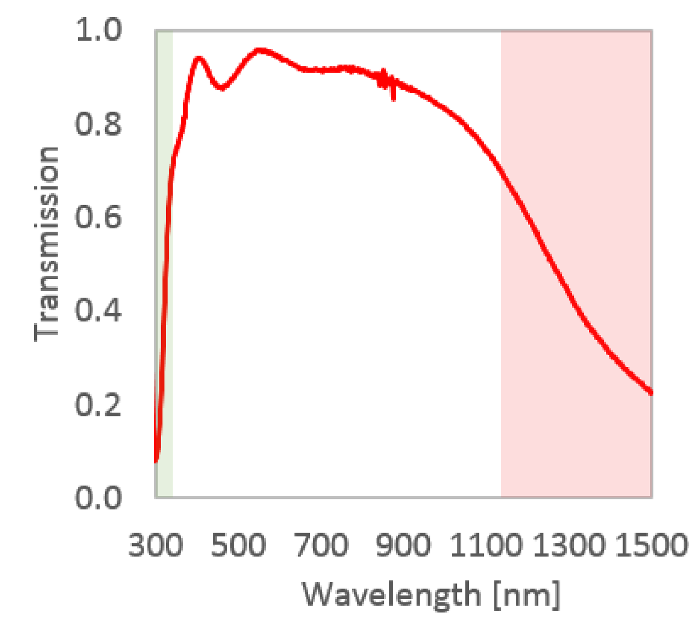




Oxygen Deprived AZO

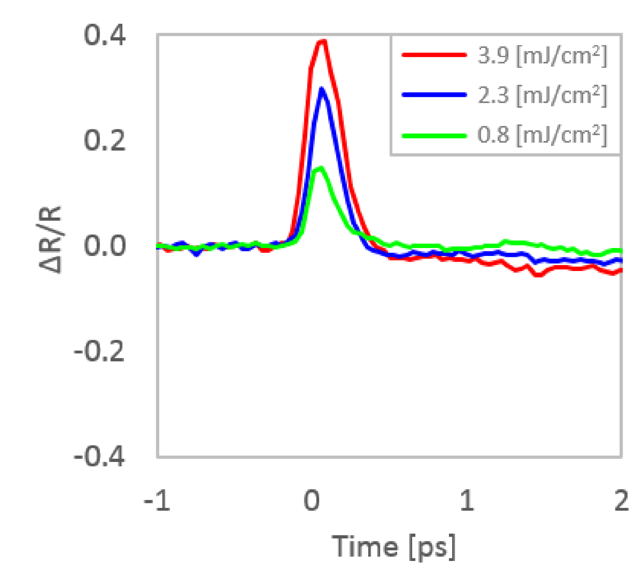
TCOs have the ability to support large doping concentrations (~10^{20} cm^{-3}), but even higher doping is required to achieve plasmonic properties at the technologically important telecom wavelengths. By depositing our aluminum doped zinc oxide (AZO) films under a low oxygen partial pressure, a high density of oxygen vacancies is created, leading to an even higher carrier concentration of ~10^{21} cm^{-3}.

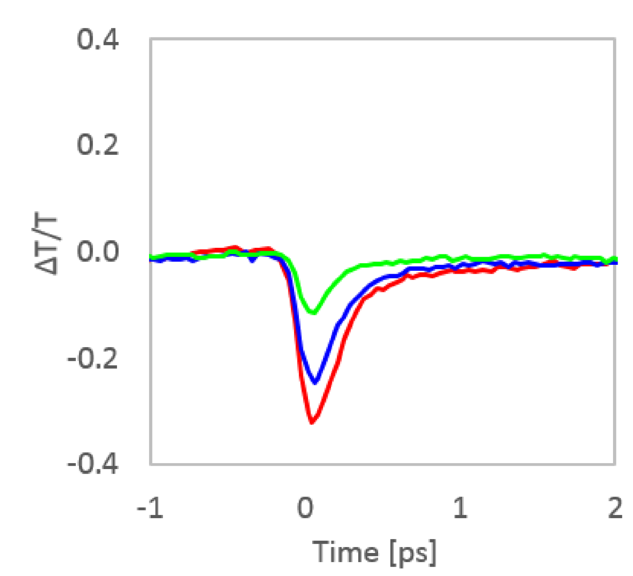




Experimental Results

A 350 nm AZO film is pumped above the bandgap energy at a wavelength of 325 nm to generate free electron-hole pairs. In turn, these free electrons contribute to the Drude dispersion which modifies the optical properties of the AZO until they recombine. Our film is probed at 1.3 µm to observe the change at telecom wavelengths. We find that under a low pump fluence of 3.9 mJ/cm² a 40% (30%) change in the reflection (transmission) can be achieved which has a relaxation time of 88 fs – far beyond the traditional amplitude-bandwidth trade-off [3].

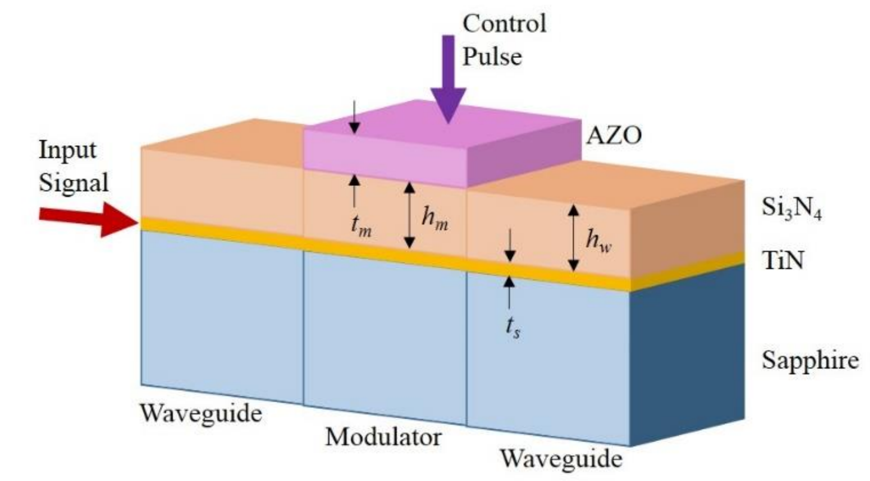


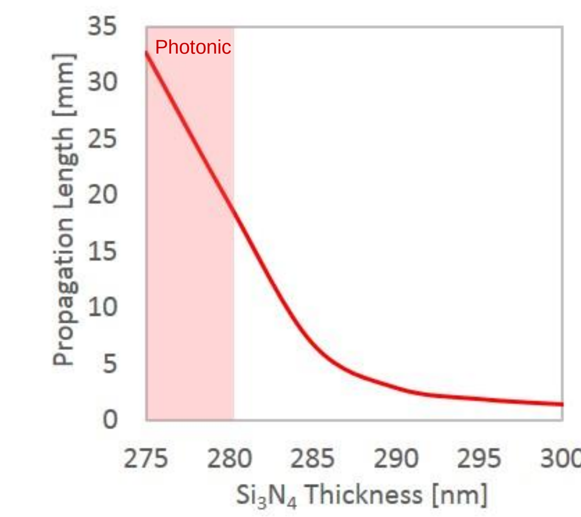


Pump Fluence [mJ/cm²]	Max. ΔR [%]	Max. ΔT [%]	Intrinsic Concentration [cm^{-3}]	Rec. Time [fs]	Avg. Induced Carriers [cm^{-3}]	AZO $\Delta n + i\,\Delta k$
1.0	15	-12	9.8×10^{20}	100	0.2×10^{20}	$-0.07 + i\,0.07$
2.4	30	-25	9.8×10^{20}	92	0.5×10^{20}	$-0.14 + i\,0.16$
3.6	39	-32	9.8×10^{20}	88	0.7×10^{20}	$-0.17 + i\,0.25$

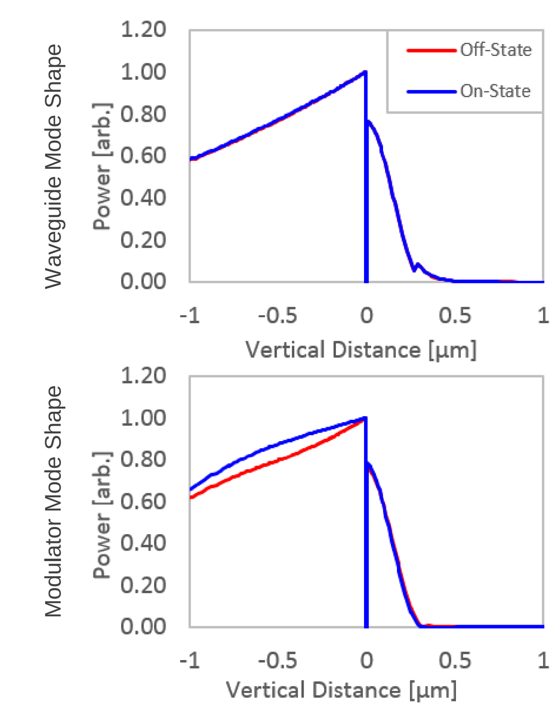
All-Optical Modulator

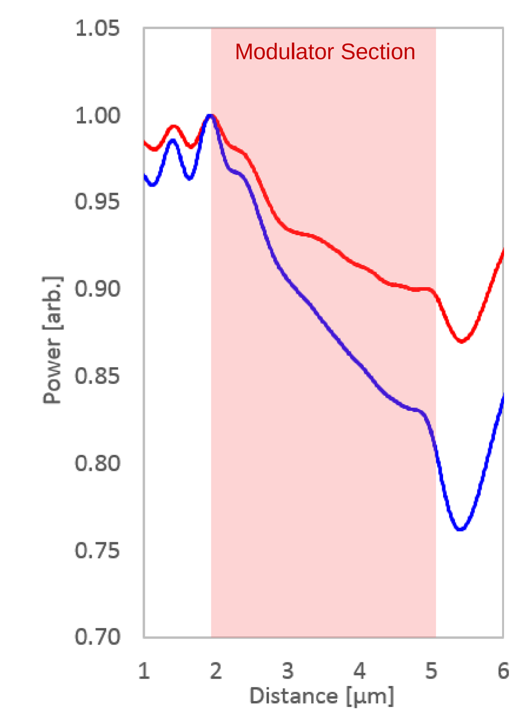
Using the experimentally verified performance, an all-optical plasmonic modulator was designed as a case study for the material. Using a low-loss TiN hybrid plasmonic-photonic waveguide as the base [4], a CMOS-compatible device is achieved. Additionally, the device is very simple, requiring only two lithography steps to fabricate.





Numerical simulations of the device were completed using the finite element method. Results of the simulation show a modulation depth of 0.4 dB/µm with an insertion loss of <0.1 dB/µm, all with experimentally verified speeds exceeding 1 THz [3]. Consequently, this device represents a viable option for integrated all-optical circuitry with unprecedented speed.





Conclusion

All-optical modulation is critical for future high-performance devices. However, many materials are limited by either their small response or slow recombination. Here we present an oxygen-deprived AZO film specifically designed to increase the optical response and recombination time. The result is a drastic increase in the performance, more than an order of magnitude compared to other materials. Consequently, our oxygen-deprived AZO film meets all of the ideal properties of a dynamic material required for next generation all-optical devices.

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[2] S. Gupta et al, IEEE J. Quant. Electron. **28**, 2464 (1992).
[3] N. Kinsey et al, arxiv 1503.07832 (2015).
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