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RadSensor: Optical Dielectric-Modulation Sensing of Ionizing Radiation for Diagnostics for Weapons Physics Ignition Experiments

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RadSensor: Optical Dielectric-Modulation Sensing of Ionizing Radiation for Diagnostics for Weapons Physics Ignition Experiments

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Objective and Goal

The objective of this program is to investigate and develop a novel class of high speed single transient ionizing radiation detector technologies that will enable critical diagnostics for the Stockpile Stewardship Management Program (such as ignition and other experiments) that is currently lacking. The goal is to achieve temporal resolution in the ~100 fs to 1 ps range, provide adequate fidelity to accurately measure DT burn histories, and extrapolate these to probable impact on nuclear weapon phenomena. This detector concept will be capable of femtosecond temporal response, good sensitivity (single x-ray photons), and can be fabricated into imaging arrays.

Motivation

The Ignition Weapons Physics Working Group was charged with exploring weapons physics issues that would take advantage of NIF's ignition goals. The history of relevant experiments performed at the Nevada Test Site (NTS) clearly indicates that the very high bandwidths are needed to accurately measure capsule reaction histories. This bandwidth was not available in the past, so theoretical predictions have gone untested. A simple spatial scaling calculation on the smaller NIF capsule geometries leads to the conclusion that measurement bandwidths in excess of 1 THz will be required. This capability currently does not exist. If successful this recording technology will enable experimental investigations and code verifications into this important physics regime.

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Scope

Single-shot ionizing radiation instrumentation that is capable of ~100 fs temporal resolution and sufficient fidelity to perform necessary reaction history measurements poses an extremely challenging technology development problem. Our overall approach has been to separate the problem into two components: RadSensor and FemtoScope. The first of these components form the focus of this project. Our philosophy recognizes up-front that optical techniques (guided-wave where possible) will be the most likely approach to succeed in solving this extremely challenging problem.

The RadSensor represents a new class of radiation detector. It's purpose is to convert the difficult problem of detecting and recording a modulated ionizing radiation beam to the simpler task of recording a modulated optical beam. This is accomplished by using the ionizing radiation to modulate an optical carrier beam (that will be sourced by a low-noise solid state laser). The most-likely class of candidate detectors will use the ionizing radiation beam to phase modulate the optical carrier. This phase modulation will be further processed through guided-wave interferometry to produce an amplitude modulation.

This amplitude modulated optical signal now needs to be recorded and digitized. For this we leverage emerging developments in nonlinear guided-wave optics to invent and develop a new class of ultrafast single-transient recorder, which is the FemtoScope and comprises another LDRD project.

This project addressed those high-risk physics, engineering, and technology issues that will be enablers of the RadSensor. If this program is successful, programmatic funds can be used to develop a fieldable RadSensor with vastly lowered technical risk.

Technical Approach

This new detector will be based on state-of-the-art photonics technologies; its development will combine basic materials research, Monte Carlo modeling of sensitivities, III-V semiconductor growth and processing techniques, and advanced photonics packaging and system integration.

Ionizing radiation will produce hot or ballistic electrons upon interaction with matter. Our proposed detector concept is based on the notion that these "hot" carriers when introduced into a semiconducting medium will efficiently produce electron-hole pairs that will result in an index change proportional to the absorbed ionizing radiation energy. Through interferometry, this index change can then be used to modulate the amplitude of an optical carrier. Since the original inception, the related field of nonlinear optics in semiconductors has made significant progress. This recent progress greatly reduces the risk of development for this innovative detector concept.

We note that the optical index modulation in our detector shares most of the electron dynamics inherent in many semiconductor-based nonlinear all-optical switches (see Ironside[i] for an excellent review, as well as Garmire[ii]). In this field the fundamental goal is the development of all-optical switches and gates that allow one optical beam to "switch" or gate the transmission of a second optical beam. In our radiation detector, the radiation beam plays the role of the optical pump in the all-optical switch.

The Ippen[iii] group at MIT has done significant work in understanding the underlying electron dynamics of several semiconductor-based switches. There are several examples now in the literature of all-optical switches that are able to optically switch with 1pJ of optical energy and with a temporal response of 1 ps. Recently the Ippen group announced a switch with < 100 fs response and a switching energy <100 fJ[iv].

We can use these switching energy results from the all-optical switching field to estimate the sensitivity of our detector approach. If we assume a modest optical carrier beam power of 2 mW, this will provide more than 10^4 photons/ps, which provides a shot-noise limited amplitude resolution of 1% with 1 ps temporal resolution. Thus we should be able to resolve 1% of the switching swing of the detector with a modest optical carrier power of 2 mW. Given a total (full swing) switching energy of 100 fJ (which is consistent with the best reported) we should thus be able to detect an absorbed energy of 1fJ (1%), or ~ 6 keV. We note that this approach should allow us to come close to counting 10 keV photons. Higher energy photons may yield nearly single-photon detectivity provided ~ 6 keV can be deposited within the active detector volume. Thus, we are hopeful that this detector approach will yield excellent sensitivity.

Further, we note that a likely interferometer geometry will be a Fabry-Perot structure much like a vertical-cavity surface emitting laser (VCSEL). In fact, all-optical switches of impressive performance have been demonstrated with precisely this geometry[v]. This type of detector is very amenable to the production of arrays. The detector cavities are in fact "grown" by epitaxial growth an entire wafer at a time. Wafer sizes large enough to accommodate 10^6 pixels are within the scope of the existing state-of-the-art, though further developments in uniformity will no doubt be required.

Accomplishments in FY99

We made significant progress toward our fundamental goal of demonstrating and characterizing the RadSensor optical index modulation with ionizing radiation input. The RadSensor characterization experiments have been designed for two main types of short pulse excitation sources

- Low energy, table top source:
  - Optical excitation (few eVs)
  - E-beam excitation (few keVs)
- High energy, short pulse radiation source:
  - User facility (up to a few MeVs)

The table-top sources were assembled and characterized in our optics labs. This will enable their use in conjunction with our femtosecond spectroscopic capabilities that we developed for this project. In the second radiation source environment (user facilities), we must have a high-bandwidth optical recording system and a robust and stable laser carrier source. This basic testbed is shown in fig. 1. To characterize RadSensor with adequate temporal resolution consistent with single-shot recording, the optical streak camera is the best extant recording technology.

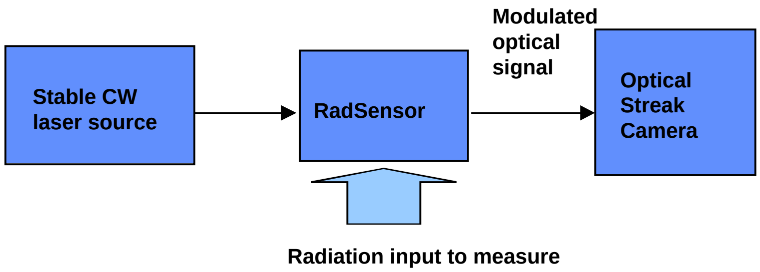


Figure 1. Required RadSensor radiation characterization testbed.

However, the optical streak camera places rather severe constraints on the wavelength of operation. This impacts both the material system that can be used for the RadSensor and the optical carrier source. We previously demonstrated that low-temperature grown GaAs (LT-GaAs) has a very fast temporal response (carrier relaxation time), see figure 2 below, and we considered it a prime candidate material for RadSensor.

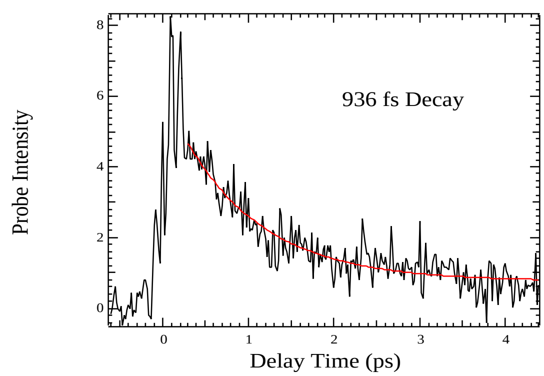


Figure 2. Temporal response of LT-GaAs optical index under optical excitation.

Indeed, the LT-GaAs family and related materials are still of significant interest. However, LT-GaAs has a bandgap (~ 870-900 nm) that is too small for effective streak camera recording. Comparing the bandgap to the spectral responsivity of an S20R streak camera photocathode (see Figure. 3), it becomes clear that operating below the bandedge to avoid material absorption will access the low range of the streak camera sensitivity. Analysis of the convolution of figure 3 with absorption spectra of a typical LT-GaAs sample indicates that the maximum optical signal QE would be too low to be useful with optical carrier sources of reasonable power.

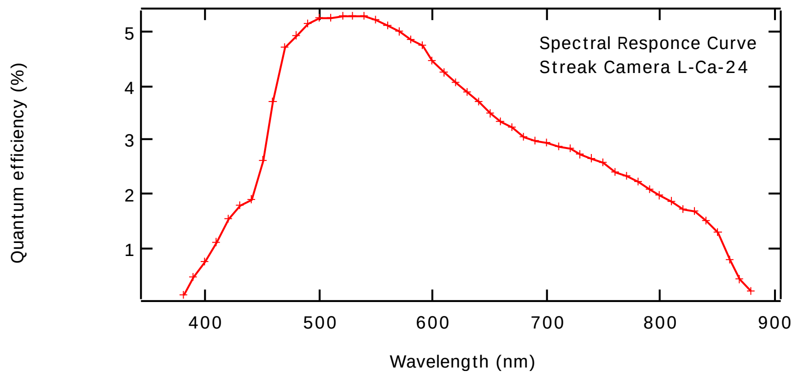


Figure 3. Streak camera spectral response.

Thus to enable the RadSensor testbed of fig. 1, we must engineer new materials that have the temporal response of LT-GaAs while maintaining a bandgap that is large enough to allow effective use of streak camera recording.

Our approach to this bandgap engineering for RadSensor was to use both alloy composition and quantum effects (quantum wells and superlattices). Our work thus far has focussed on the materials illustrated in fig. 4.

Figure 4. Bandgap engineered materials for RadSensor

Parameters to evaluate in the material growth include growth temperature, anneal temperature and staging (postgrowth or *in situ*), n^+ vs. semi-insulating substrate, and alloy composition. To evaluate these engineered materials and their large parameter space we used optical experiments to understand their bandstructure, including defect levels, and carrier dynamics. The physics issues are complex and illustrated in fig. 5.

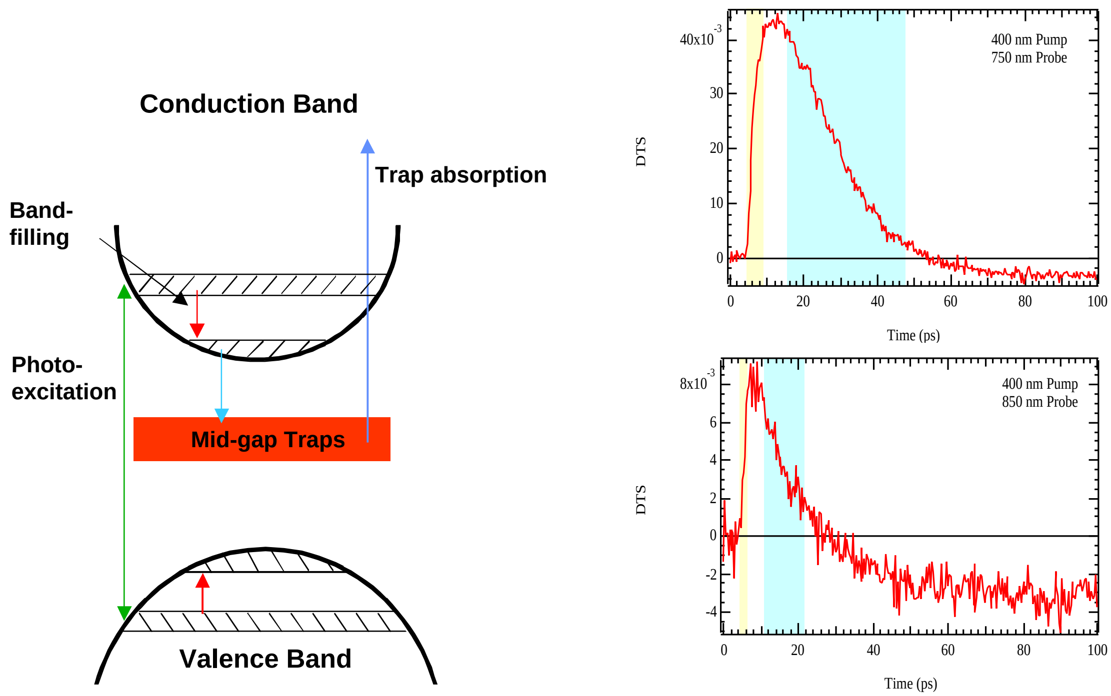


Figure 5. Pphysics of low-temperature grown materials and the temporal response of LT-AlGaAs Quantum Well material.

The ultimate temporal resolution of RadSensor is determined by the carrier dynamics of the nonlinear material. The carrier dynamics are studied through time resolved changes in the transmission spectra (differential transmission spectra, DTS) using femtosecond pump-probe spectroscopy. As illustrated in figure 5, there are two principal manifestations of the carrier dynamics: bleaching and trap absorption (mediated by Arsenic precipitates). Bleaching results from the optical excitation of carriers into the excited states of the conduction band (state filling) and decays through the relaxation of excited carriers to the bottom of the conduction band (bandfilling). These carriers then relax into traps located in the midgap region. Trap absorption results from the optical excitation of these traps (As precipitates) into the conduction band. Both processes contribute to the change in the index of refraction (nonlinear index). However, the index change from hot carriers and carriers at the bottom of the conduction band may dominate, whereas the index change from the trap population may be minimal. The temporal response of the nonlinear index from these processes may also be different. Our goal is to engineer a subpicosecond time response of the index of refraction from these nonlinear materials.

Figure 5 also shows the results of femtosecond pump-probe spectroscopy on LT-AlGaAs quantum wells with probe wavelengths at 750 nm (above the bandedge) and 850 nm (at or below the bandedge). The relaxation of the optically excited carriers to the bottom of the conduction band (bandfilling) is given by the rise time of the bleaching signal (outlined in yellow) and occurs in 2-4 ps. The trapping is given by the decay of the bleaching signal (outlined in blue) and occurs in 9-34 ps. Finally the relaxation of the traps occurs in ~ 100 ps. These results show two major shortcomings of this material system: the band gap energy is too low, and the response times are too long.

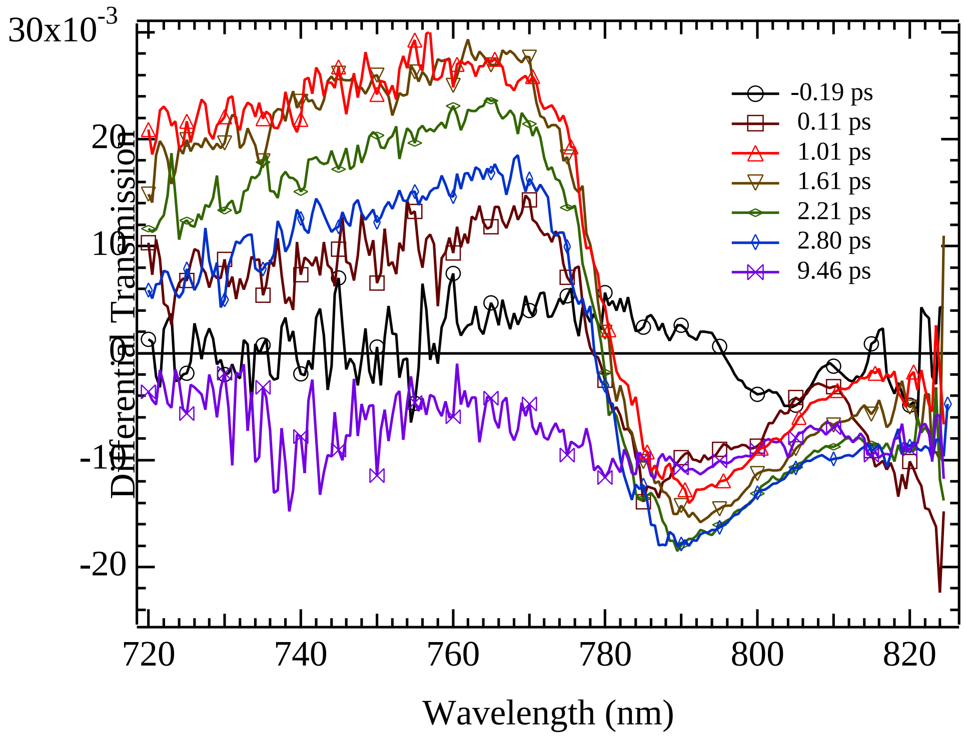
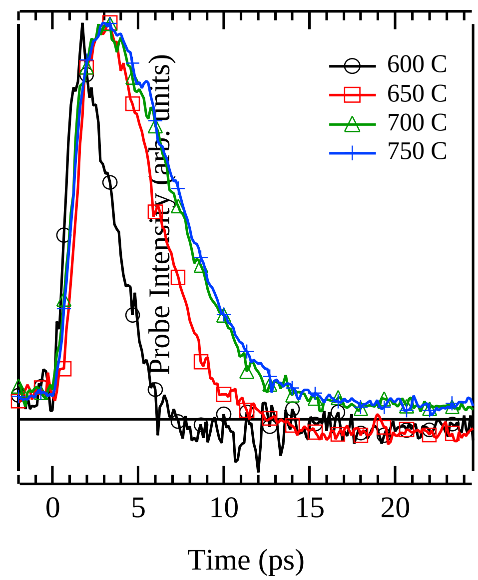


Figure 6. Differential transmission spectra of low temperature grown AlGaAs (LT-AlGaAs) taken at various temporal delays after optical excitation. Delay times re indicated. The data indicates an effective bandgap of ~780-800 nm, which is ideal for streak camera analysis.

As a result of these problems with the LT-AlGaAs quantum well system, we considered bulk LT-AlGaAs as an alternative material system. Figure 6 shows time resolved differential transmission spectra of LT-AlGaAs after 400 nm optical excitation. In this case, the time response of the bandfilling process is greatly improved over the quantum well system and occurs in ≤ 1 ps, as given by the rise time of the bleaching signal (positive feature). Carrier trapping is also faster and occurs in 2-3 ps, as given by the decay of the bleaching signal. These operating parameters for the LT-AlGaAs system are very promising and may be further improved through additional materials engineering and processing, if needed.

We established a firm understanding of the device/materials processing parameters and the design space for bandgap engineered quantum well devices and materials, including the effects of growth temperature, anneal temperature/time, and growth substrates. Figures 7 and 8 shows how the post-anneal temperature affects the material response time. Post annealing provides an effective method to control the temporal response times of LT-AlGaAs by controlling the bandfilling and trapping times. Our results show that the response times shorten with decreasing post anneal temperature. Tools are in hand to engineer the time response and operating wavelength of the device.



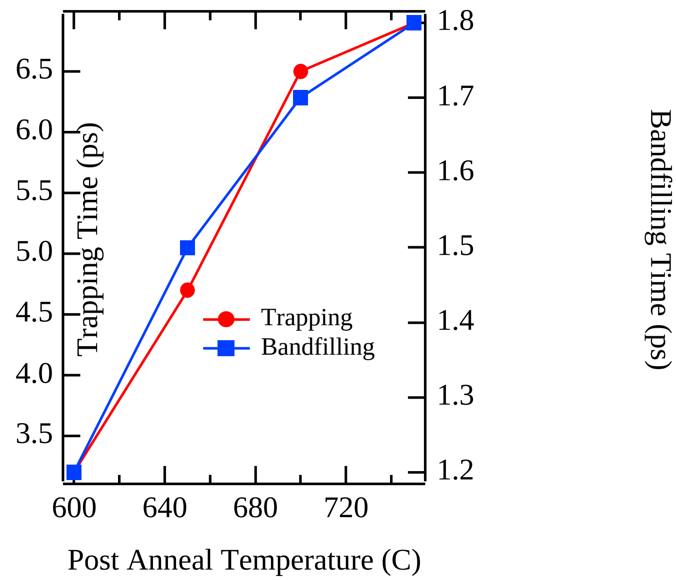
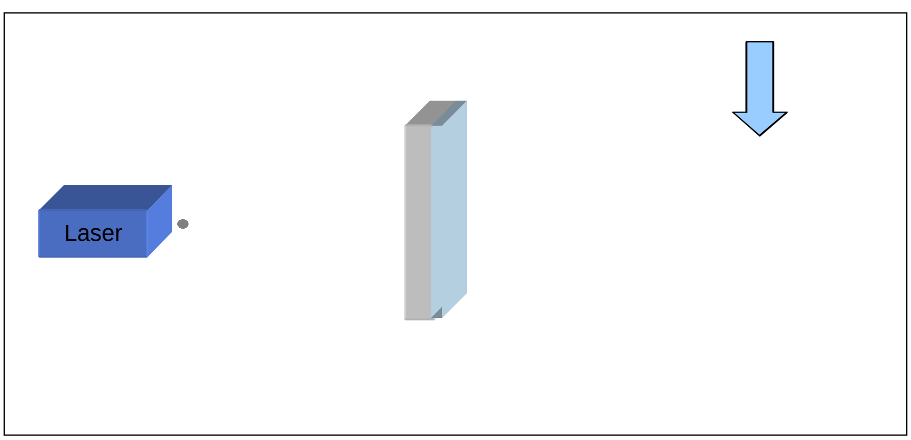


Fig. 7 Effect of the post-anneal temperature on the carrier relaxation near the bandedge of LT-AlGaAs.

Fig. 8 Effect of the post-anneal temperature on the bandfilling time and the trapping time of LT-AlGaAs.

Finally, we pursued dual paths for the development of a table-top e-beam source for RadSensor radiation characterizations in our optics lab. Our first approach is to use a cw-beam and sweep the beam past a mask to generate ps pulses of electrons. To reduce risk, we also pursued a laser driven pulsed e-beam source illustrated in figure 9. Here a short intense laser pulse irradiates a photocathode that is biased with a very high electric field from an extraction grid. A short electron pulse is emitted and accelerated up to 20 keV. Both sources are nearing completion.



In summary, we established a comprehensive device characterization strategy that involves sophisticated optical characterization, e-beam characterization, and a testbed concept to evaluate RadSensor at short-pulse radiation user facilities. We developed a complex set of optical femtosecond spectroscopies to evaluate our materials and devices. We developed the processing technology for 4 classes of RadSensor materials and characterized these materials. This materials and device development effort yielded several promising candidates that are compatible with streak camera recording. The next stage of this diagnostic development will involve the demonstration of optical carrier modulation under short pulse e-beam or x-ray excitation.

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[i] Ironside, "Ultra-fast all-optical switching," Contemporary Physics, vol. 34, no. 1, pp. 1-18 (1993).

[ii] Garmire, "Nonlinear Optics in Semiconductors," ***Physics Today***, pp. 42-48 (1994).

[iii] K.L. Hall, A.M. Darwish, E.P. Ippen, U. Koren, and G. Raybon, "Femtosecond index nonlinearities in InGaAsP optical amplifiers", ***Appl. Phys. Lett.*** , **62** (12), 1320(1993).

[iv] This result is from a private communication from Rauschenbach to M. E. Lowry and has not yet been published.

[v] Takahashi, Y. Kawamura, and H. Iwamura, "Ultrafast 1.55 μm all-optical switching using low-temperature-grown multiple quantum wells," ***Appl. Phys. Lett.***, **68** (2), 153(1996).