Optical Dephasing and Acoustic Plasmon Undamping in Highly Excited Semiconductors

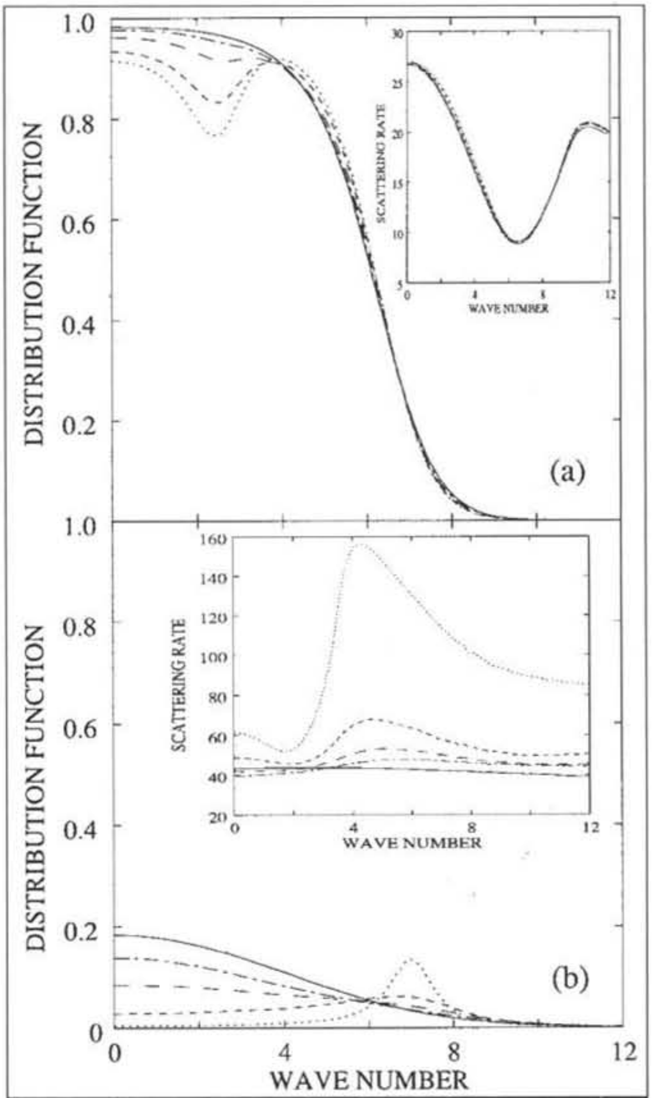
By S.W. Koch, D.C. Scott, and R. Binder, Optical Sciences Center and Physics Department, University of Arizona, Tucson. Ariz.

Optical dephasing, *i.e.*, the decay of the polarization field in a semiconductor, is a direct consequence of electron and hole scattering. Under high excitation conditions or in a semiconductor amplifier/laser, carrier-carrier scattering is often the dominant relaxation mechanism, which also leads to energy-level broadening and dynamical screening of the Coulomb interaction potential. The theoretical analysis of carrier-carrier scattering is based on the quantum Boltzmann equation. Even though this equation is well known in the many-body literature,[1] its solution for high excitation conditions and nonequilibrium carrier distributions is a substantial challenge.

To study nonequilibrium carrier relaxation and optical dephasing, we performed direct numerical integrations of the time-dependent Boltzmann equation where the dynamical screening of the Coulomb interaction potential was consistently treated at the same level as the scattering probabilities.[2,3] The solution of the quantum Boltzmann equation yields the dynamic changes of the electron and hole distribution functions. These changes can be expressed in terms of scattering rates, which determine the average time an electron or hole remains in a quantum state. In generalization of the well-known relation between optical dephasing and excited state lifetime in atomic systems, the sum of the "lifetimes" of the semiconductor electrons and holes in a state determine the dephasing of that state.[2,3]

We studied the carrier dynamics and optical dephasing for an optical semiconductor amplifier, *i.e.*, an inverted semiconductor where the carrier density is sufficiently high to allow a spectral region of optical gain. The amplification of an incident light beam leads to a frequency dependent depletion of the inversion, *i.e.*, to a "hole" in the distribution function. Studying the relaxation of such a "kinetic hole," we obtained carrier relaxation and optical dephasing times of the order of 50 fsec for carrier densities, typical for amplifier or laser operation conditions in GaAs.[2] The figure shows an example of the dynamic evolution of the electron distribution function. The corresponding scattering rates are essentially time independent. The momentum-dependence of these scattering rates reflects the phase-space restriction near the Fermi edge, which is strongly smeared out in this case.

A very different situation occurs for femtosecond excitation of passive semiconductors, energetically high in the region of optical interband absorption. For the generated nonequilibrium plasma, we find significantly reduced relaxation times, which can be as short as 10 fsec.[3] In Part B of the figure, we plot the relaxation of the nonequilibrium electron-hole plasma distribution. The dynamic scattering rates (inset) exhibit a very strong momentum dependence with pronounced peaks corresponding to dephasing times around



Numerical solutions of the electron-hole Boltzmann equation using the dynamically screened Coulomb potential in random phase approximation. The figure shows only the electron distributions at different times; the full electron-hole relaxation dynamics can be found in Refs. 2 and 3. (a) Relaxation of initially disturbed Fermi distribution functions for density n = 3×10^{18} cm^{-3} and temperature T = 300 K. Shown is the electron distribution as function of the carrier momentum in units of the exciton Bohr radius (a_B). The initial (t = 0) distribution function is plotted as a dotted line. Consecutive times are t = 21 fsec (short-dashed), t = *75* fsec (long-dashed), and t = *147* fsec (dash-dotted), and the final time t = *796* fsec (solid). (b) Relaxation of initial nonequilibrium distribution for density n = 4.6×10^{17} cm^{-3}. The initial (t = 0) curve is plotted as a dotted line. Consecutive times are t = 70 fsec (short-dashed line), t = 185 fsec (long-dashed line), t = 355 fsec (dash-dotted line), and the final time t = 1590 fsec (solid line). The insets show the corresponding scattering rates in ps^{-1}.

10 fsec. We find that such extremely high scattering rates occur only for carrier configurations that allow the undamping of the acoustic plasmon resonance,[3] which is strongly Landau damped under equilibrium conditions. Our analysis shows that the acoustic plasmon undamping for nonequilibrium distributions causes the enhancement of the scattering matrix element leading to ultrafast relaxation and optical dephasing.

ACKNOWLEDGMENT

Part of this work was done in collaboration with A. Paul, M. Lindberg, and K. Henneberger. These projects are supported by grants from NSF, ARO, AFOSR, and the Pittsburgh Supercomputer Center.

REFERENCES

1. L.P. Kadanoff and G. Baym, *Quantum Statistical Mechanics*, Addison-Wesley, 1989; G. D. Mahan, *Many-Particle Physics*, Plenum, New York, N.Y., 1986.
2. R. Binder *et al.*, "Carrier-carrier scattering and optical dephasing in highly excited semiconductors," Phys. Rev. B **45**, 1992, 1107-1115.
3. D.C. Scott *et al.*, "Ultrafast dephasing through acoustic plasmon undamping in nonequilibrium electron-hole plasmas," Phys. Rev. Lett. **69**, 1992, 347-350.

▶ Call for Authors

Optoelectronics Series

You can enhance your professional prestige and earn substantial royalties by authoring a book. Artech House, a leading professional-level technical and engineering publisher, is currently seeking new authors for its series of optoelectronics books. Under the aegis of Series Editors Brian Culshaw, Alan Rogers and Henry Taylor, the series is intended as an applications-oriented resource for engineers and scientists working in such areas as optical components and devices, fiber optics, lasers, optoelectronics, ultrafast optical phenomena, optical information processing, optoelectronic materials, and related technologies.

If you have published technical papers, conducted professional seminars or solved important real-world problems, you are an excellent candidate for authorship.

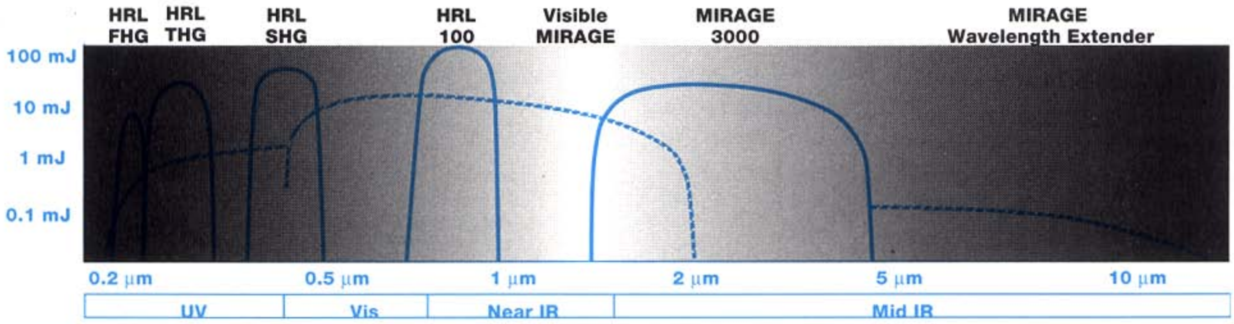
To submit a proposal or to request an Author's Questionnaire and publications catalog, please contact:

Mark Walsh, Editor
Artech House
685 Canton Street, Norwood, MA 02062
1-800-225-9977

Artech House
A Horizon House Company

STI OPTRONICS

COVERING THE SPECTRUM WITH SOLID-STATE LASERS



2755 Northup Way, Bellevue, WA 98004 USA
Tel: 1-800-4TUNING or (206)827-0460 • FAX: (206)828-3517