Direct observation of Landau damping in a solid state plasma

M. P. Hasselbeck¹, D. Seletskiy¹, L. R. Dawson¹, and M. Sheik-Bahae¹

¹ Department of Physics and Astronomy, University of New Mexico 87131, USA
² Center for High Technology Materials, University of New Mexico 87106, USA

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We report results of experiments in which we observe the clear onset of Landau damping in a homogeneous electron-donor ion plasma of a bulk semiconductor. Ultrashort laser pulses initiate coherent slab plasma oscillations, which emit far-infrared radiation into free space where it can be detected. Using a sequence of decreasing thickness (d) InSb heterostructures, the scattering wave vector (q) in the electron-electron interaction is increasingly restricted (i.e. \( q \approx 1/d \)) , which strongly damps the coherent plasma radiation. The semiconductor InSb is an excellent system for an experimental study of coherent plasmon damping because of its high mobility and – unlike InAs – it can be grown with much higher purity. This leads to long-lived coherent plasma oscillations [4].

To understand the problem and estimate the length scales, we calculate the electron-electron interaction in bulk n-InSb at an electron and lattice temperature of 77 K [5]. The model incorporates conduction band non-parabolicity and Fermi-Dirac statistics. Plasmons are longitudinal modes of the polarization that can be identified graphically as poles of the reciprocal momentum- and frequency-dependent dielectric function \( \text{Im}(\epsilon(q,\nu)) \). Electron mobility is incorporated via the Lindhard-Mermin formulation of \( \epsilon(q,\nu) \) [1]. Results of this calculation for bulk n-InSb with donor doping of \( 1.2 \times 10^{15} \) cm\(^{-3} \) are presented in Fig. 1. At small scattering wave vectors (\( q \approx 0 \)) corresponding to an infinite, bulk semiconductor, a distinct plasmon is evident at \( \nu = 0.6 \) THz. The plasmon linewidth here is determined by the bulk mobility, which we set with a momentum relaxation rate of 1.7 ps\(^{-1} \) appropriate for our samples. For scattering wave vectors \( q > 2 \times 10^{4} \) cm\(^{-1} \), the calculation shows pronounced Landau damping of the plasmon accompanied by a blue-shift of the center frequency. This suggests that restricting the physical size of the InSb crystal along the direction of oscillation could reduce or eliminate coherent plasmon motion.

To explore this idea experimentally, we grow a series of high quality crystalline heterostructures using molecular beam epitaxy. A top layer of InSb is separated from the (100) InSb substrate by a 40 nm barrier of \( \text{Al}_{0.1}\text{In}_{0.9}\text{Sb} \). The energy barrier in the conduction band is estimated to be \( > 80 \) meV, which isolates electrons in the top layer from the...
thick substrate. Five structures are fabricated having InSb layers with varying thicknesses $d = 200, 350, 500, 650, \text{ and } 1500 \text{ nm}$. These dimensions are chosen to map out the behavior depicted in Figure 1. Note that these layers are too wide to induce quantum-confined electronic levels, i.e., quantum wells. The donor density in the top InSb layers is kept constant at $1.2 \pm 0.1 \times 10^{15} \text{ cm}^{-3}$.

The experimental setup is shown in Fig. 2 and follows Kersting et al. [6, 7]. Autocorrelation signals are generated using a Michelson interferometer arrangement. Two pump pulses from a mode-locked Ti:sapphire laser (duration: 60 fs; center wavelength: 820 nm) are focused on the sample at a 45° angle of incidence and slightly separated positions with adjustable delay. The data is not sensitive to the linear laser polarization. The semiconductor structures are held at a temperature of 77 K in an optical cryostat. The emitted electromagnetic radiation is collected in the specular direction and detected with a liquid-He cooled Si bolometer. The interferometric signals are not phase-resolved, but do provide the frequency and coherence length of the far-infrared electromagnetic pulse.

THz emission from narrow gap semiconductors can be generated in a variety of ways. Non-phase matched optical rectification of the ultrashort pump pulse spectrum is predominant at high irradiance. The far-infrared power changes depending on the orientation of the laser polarization relative to the crystal axes. This is explained by the spatial dependence of the second-order nonlinear susceptibility tensor $\chi^{(2)}$ [8]. At lower irradiance, optical rectification largely disappears allowing radiation from ultrafast carrier transport to be studied. Ultrashort pulses of near-infrared radiation are strongly absorbed in opaque semiconductors, creating a high concentration of hot photocarriers immediately below the surface (penetration depth: $< 100 \text{ nm}$ [9]). Ultrafast, ambipolar diffusion of these electrons and holes produces a macroscopic charge dipole that emits a broad bandwidth, far-infrared pulse into free space [10]. This photo-Dember current also results in a space-charge field that can Coulomb-couple to mobile carriers in the bulk. If the risetime of this Dember field transient is short compared to the plasmon period, coherent collective oscillations can be started as cold electrons move to screen the perturbing field [4, 7, 11]. These oscillations are macroscopic dipole fields that emit far-infrared radiation originating from a distinctly different physical phenomenon. In our experiments, an ultrafast photo-Dember field initiates coherent plasma oscillations of cold electrons in the bulk. It is important to emphasize that radiation resulting from the diffusion of an inhomogeneous, hot photocarrier distribution (estimated density: $\sim 10^{18} \text{ cm}^{-3}$) is not directly measured with our interferometric arrangement [4]. In addition, the photocarriers have negligible penetration into the underlying layers – even for the thinnest samples studied – ensuring that the radiation signals emanate exclusively from the top InSb layer. Light emitted by coherent LO phonons (5.9 THz) cannot be observed due to the high frequency cutoff of the MgF$_2$ cryostat window ($\sim 3 \text{ THz}$).

Autocorrelation signals from our experiment are presented in Fig. 3. The 1500 nm sample produces several plasma oscillations at 0.6 THz consistent with the calculation in Fig. 1 for a semi-infinite plasma ($q = 0$). The coherent plasmon signal decays in $\sim 5 \text{ ps}$ mainly due to incoherent LO phonon scattering [4]. With decreasing layer thickness, the scattering wave vector in the electron-electron interaction is increasingly restricted and collective, plasmonic behavior weakens. The signal amplitude decreases, fewer os-
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Figure 3 Autocorrelation scans of far-infrared radiation emitted by five different InSb heterostructures (T = 77 K) of varying thickness as indicated. Blue-shift of the plasma frequency is depicted with dashed reference lines. The signals are plotted on the same relative scale and displaced vertically for clarity.

oscillation cycles are resolved, and a blue-shift of the plasma frequency by an amount $\Delta \nu = 140 \sim 50$ GHz is observed (dashed reference lines in Fig. 3). All this behavior is completely consistent with the Landau damping model of Fig. 1, which predicts a positive frequency shift of $\Delta \nu \sim 100$ GHz.

We wish to distinguish between Landau damping and the decay of coherent plasmon motion that could occur at the hetero-interface, i.e. scattering at the AlInSb barrier. For the latter effect to be important, the amplitude of coherent plasmon displacement would have to be comparable with the thickness of the InSb layer. This amplitude is found by solving the Lorentz-Drude equation of motion for the slab plasmon in the absence of Landau damping [7]:

$$\frac{d^2}{dt^2} x(t) + \gamma \frac{dx}{dt} x(t) + \omega_p^2 x(t) = \frac{e}{m^*} E(z, t)$$

where $\omega_p$ is the bulk plasma frequency, $m^*$ is the electron effective mass (donor ions are assumed to be stationary), $\gamma$ is the momentum relaxation rate, and $E(z,t)$ is the time- and spatially-varying ultrafast Dember field transient. A realistic model of this electric field is problematic, however, because it must incorporate the temperature, mobility, and diffusion coefficients of extremely hot photocarriers in at least four different bands [7, 10].

We can place an upper limit on the photo-Dember field by noting that inter-valley transfer of conduction electrons in InSb occurs at ~ 500 V/cm accompanied by drastically reduced mobility [12]. This scattering occurs on a timescale that is short compared to the plasma oscillation period [13]. Solving Equation (1) assuming a peak amplitude of 500 V/cm and 50 fs risetime for $E(z,t)$ provides an upper limit estimate for the maximum coherent plasmon displacement of ~ 250 nm. We conclude that spatial restriction of ballistic motion in the heterostructure is only a concern for the thinnest sample used in our experiments.

It has been shown that scattering between charge carriers of different effective mass can contribute to loss of coherence in plasma oscillations [14, 15]. The present experiments involve a cold plasma defined by mobile conduction electrons bound to fixed donor ions. This means that scattering between the oscillating electrons and a spatially inhomogeneous distribution of hot holes injected by the pump laser can play a role in the observed damping. By varying the excitation irradiance and hence the photo-carrier density, we determine that electron-hole scattering makes a minor contribution to the coherent plasmon dephasing in Fig. 3.

Slab plasmons are longitudinal modes of the polarization, which means they are infrared inactive, i.e. they should not couple to free-space electromagnetic radiation. In our experiments, however, the radiating volume is much smaller than the free-space wavelength. The coherent plasmon oscillation can be treated as a Hertzian dipole antenna that gives rise to a propagating transverse electromagnetic wave [16].

In summary, we have made direct observation of Landau damping in a bulk semiconductor. A spatially homogeneous electron-donor ion plasma is coherently excited by ultrashort laser pulses. The cold plasma radiates an electromagnetic wave into free space, where its coherence properties are measured. By restricting scattering to occur with high momentum wave vectors, collective plasma behaviour is lost – the plasma becomes Landau damped. Landau damping is accompanied by a blue-shift of the plasma frequency.

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References


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