Observation of the Burstein-Moss Effect in GaAs Wafers via Few-Cycle Transient Dispersion Measurement

Rui Zhou*, Hemang Jani, and Lingze Duan
Department of Physics and Astronomy, The University of Alabama in Huntsville, Huntsville, AL 35899, USA
**Corresponding author: rz0006@uah.edu*

Abstract: We report time-resolved measurements of transient dispersion in GaAs wafers using few-cycle pump-probe reflectometry. Comparisons among samples show good agreement with the Burstein-Moss effect model.

1. Introduction

Burstein-Moss (BM) effect is a phenomenon observed in degenerate semiconductors, where the optical band gap blue shifts as the doping concentration increases [1,2]. It is generally understood as a consequence of band filling when the Fermi level rises into the conduction band under heavy *n*-type doping [3-6]. Meanwhile, light-induced photoelectrons can also cause similar band-filling effect [7]. The associated band-gap blue shift, which sometimes is referred to as the dynamic BM effect, has been observed by driving semiconductors with strong laser pulses [8,9]. Although the BM effect caused by doping (steady-state) and the BM effect caused by photo-excitation (dynamic) are both well studied, little attention has been given to their combined effects under the same context. The Fermi level in a degenerate semiconductor is intimately related to Coulomb screening, which in turn affects the dynamics of the photo-induced band shift [7,10]. Thus, a careful investigation into the dynamic BM effect under various levels of heavy *n*-type doping is of fundamental interest.

Recently, we have demonstrated transient dispersion measurement using a few-cycle pump-probe reflectometer (PPR) [11]. Transient dispersion refers to the rapid change of wavelength-dependent refractive index $n(\lambda)$ following an ultrafast photo excitation. It can be characterized by measuring the slight variation of surface reflectivity over a range of wavelengths using broadband (few-cycle) laser pulses as probes [12]. Since the photo-induced reflectivity change $\Delta R(\lambda,t)$ switches sign at the optical band gap [7,11], a two-dimensional (2D) map of $\Delta R(\lambda,t)$ obtained through transient dispersion measurement offers a direct visualization of band gap behaviors as carrier populations evolve.

In this work, we measured the transient dispersions of four *n*-GaAs wafer samples with different doping levels. Clear evidence of both steady-state and dynamic BM effects is observed, and a link between them is identified.

2. Experiment

The GaAs wafer samples (MTI) are single-side polished with thicknesses ranging between 0.35–0.625 mm. Three *n*-type GaAs samples are chosen with doping concentrations of 4×10^{17} cm^{-3} (Te), 8×10^{17} cm^{-3} (Si), and 3×10^{18} cm^{-3} (Si), respectively. To provide a baseline reference, an *undoped* GaAs wafer is also tested.

The few-cycle PPR system is built around a 6.5-fs Ti:Sapphire laser operating at a center wavelength of 760 nm, with an average power of 500 mW and a repetition rate of 83 MHz [11]. The pump-probe setup is designed to measure *time-resolved* reflectivity. Moreover, a series of band-pass filters with center wavelengths ranging from 700 nm to 930 nm are incorporated into the detection system to provide *wavelength-resolved* measurements. Such a design allows the PPR to perform time-frequency spectroscopy with an ~10-fs temporal resolution and a >200-nm wavelength span, which covers the nominal band gap for GaAs at 1.42 eV (~870 nm).

3. Results and Discussion

Fig. 1 shows the PPR-measured relative reflectivity change $\Delta R(\lambda,t)$ as functions of *wavelength* and *time delay* (from the pump pulse) in a 2D contour map for all four GaAs wafer samples. For each figure, the color contour represents the transient change of the surface reflectivity relative to its steady-state value, which in turn signifies the transient change of refractive index. A positive change (*yellow* region) indicates a rise of the refractive index above the steady state value, whereas a negative change (*blue* region) suggests a dip in refractive index below the steady state value. The variations of these index changes vs. wavelength (the horizontal axis) provide the so-called transient dispersion. Mapping the evolution of the dispersion over time (the vertical axis) offers insight into the ultrafast carrier dynamics inside the material and the impacts of such dynamics on material properties.

In the current study, we focus on the time-evolution of the optical band gap, which can be identified in a 2D transient dispersion map as the transition edge between the positive and the negative regions [7,11]. Dashed trend lines are added in Fig. 1(a)-(d) to indicate the approximate locations of the transition edge for each GaAs sample. A common feature across all these samples is that the optical band gap appears to experience a relaxation process, red-shifting from a shorter wavelength about 500–700 fs after the excitation pulse and eventually stabilizing at a longer

wavelength after about 10 ps. Such an observation agrees with the general picture of photocarrier-induced band gap shift, i.e., the sudden increase of the photoelectron population in the first few hundred femtoseconds after excitation causes a blue shift of the optical band gap through the *dynamic* BM effect, but then, as the photoelectron population gradually decays (due to various decay channels such as recombination), the band filling effect slowly weakens until the band gap eventually shifts back to the steady-state level. In Fig. 1, the blue-shifted and the steady-state band gap wavelengths (energy) are labeled for each sample. Based on these values, it is evident that higher doping levels lead to larger steady-state band gaps, which is the original (*steady-state*) BM effect. Therefore, the transient dispersion measurement has allowed us to show *both* types of the BM effects on the same graph. Furthermore, Fig. 1 indicates that the extent of the dynamic BM effect depends on the doping level. For example, the band gap shift caused by the dynamic BM effect in the undoped sample (Fig. 1(a)) is about 15 nm (from 886 nm to 871 nm), while for the Te-doped sample (Fig. 1(b)), this shift increases to 29 nm. Similar trend is also seen in the two Si-doped samples (Fig. 1(c) & (d)). The underlying physics for this dependence is still under investigation. However, the experimental results highlight the potential of transient dispersion measurement in studying photonic material properties.

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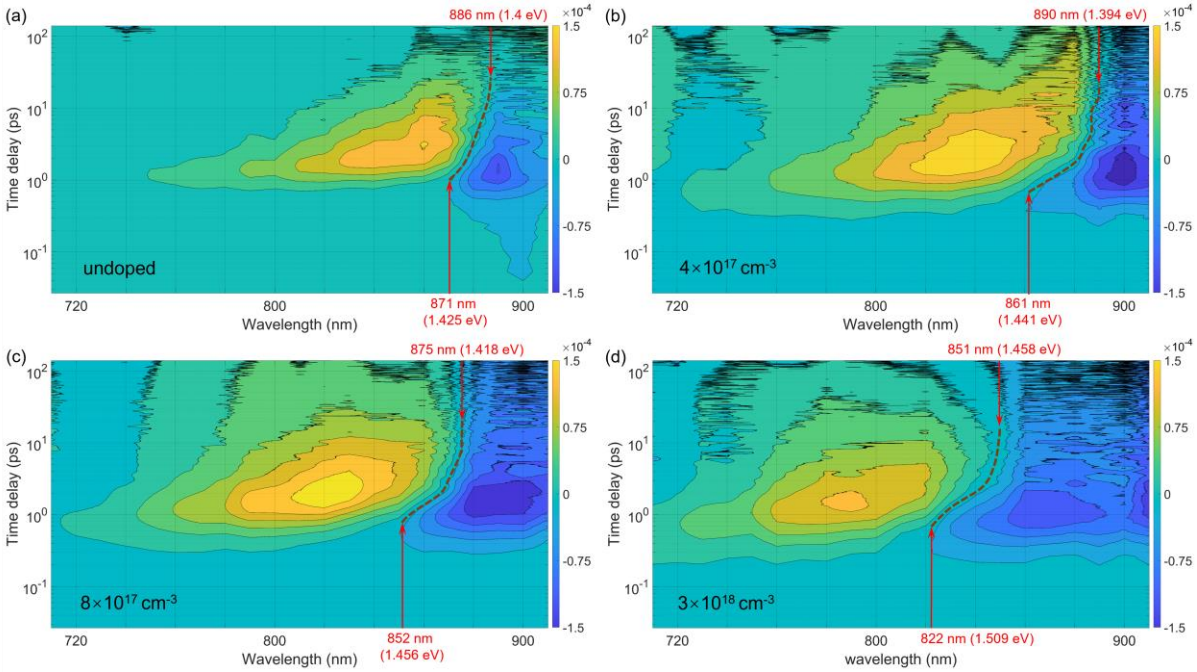

Fig. 1. 2D contour maps of the transient dispersion in GaAs wafers, measured by our few-cycle PPR system. Four samples with different doping concentrations are used: (a) undoped; (b) 4×10^{17} cm^{-3}; (c) 8×10^{17} cm^{-3}; (d) 3×10^{18} cm^{-3}. Blue-shifted and steady-state band gaps are labeled.

4. References

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