Carrier-phonon Dynamics at Buried Interface of GaP/Si(001)

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Abstract: Phonon-plasma coupling dynamics of lattice-matched GaP/Si(001) interface is investigated by photo-doping with femtosecond NUV pulses. Anti-phase domains arising from the interfaces are found to induce steep band bending within the nanometer-thick GaP film.

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1. Introduction

Incorporating the ultrafast optical response of III/V-devices within the silicon microelectronic technology has been a goal for decades. A strategy for this purpose has been the growth of direct band gap III/V semiconductors on exact Si(001) substrate. Recently, GaP layers free from dislocations, stacking faults or twins were grown on Si(001) by metal organic vapour phase epitaxy (MOVPE) [1]. However, anti-phase domains (APDs) are still unavoidable at the monoatomic steps of Si(001). At anti-phase boundaries (APBs), chemical bonds between two Ga atoms or two P atoms create charged defects. Interfaces having APDs are therefore expected to affect the device performance.

Evaluation of the electronic energy states at buried hetero-interfaces is one of the most pressing issues in device physics. Though photoemission spectroscopy is the standard technique to directly measure the electronic states of the surface, it is difficult to apply the technique to buried interfaces because the probing depth is limited to the order of nanometers.

Here we evaluate the electronic states at the buried interface of GaP/Si(001) non-destructively by detecting coherent phonons. In polar semiconductors such as GaP, one can estimate the carrier type and density from the frequency of the LO phonon-plasmon coupled (LOPC) modes [2]. Furthermore, the amplitudes of the coherent oscillations can give information on the direction and the magnitude of the built-in field within the surface depletion region. We examine specifically the effect of the APDs on the ultrafast electronic photo-response of the GaP/Si(001) interfaces.

2. Experimental

The samples studied are GaP thin films grown on Si (001) substrates by MOVPE [1] under two different growth conditions. The optimized procedure employs Si(001) substrates, with a 0.1° intentional miscut in [110] direction to form two-atomic-layer thick steps (sample I). This leads to self-annihilating APDs with P-rich boundaries on {111} planes, as shown in Fig. 1(a). We also prepare a GaP film by using a 2° miscut Si substrate, which exhibits few APDs at the interface (sample II). Cross sectional TEM images of the interfaces confirm that the GaP layers are free from dislocations, stacking faults, or twins.

Degenerate pump-probe reflectivity measurements are performed with laser pulses of 3.1-eV (400-nm) photon energy and of 10 fs duration as light source. The effective probing depth ($1/2\alpha$=58 nm for GaP) is comparable with the film thicknesses, 70 nm. Linearly polarized pump and probe beams are incident on the sample in a near back-reflection configuration. Pump-induced change in the anisotropic reflectivity ($\Delta R_{eo} = \Delta R_H - \Delta R_V$) is measured as a function of time delay between pump and probe pulses. Signal is accumulated and averaged with a digital oscilloscope while time delay is scanned repetitively.

3. Results and Discussion

Figure 1(c,d) compares the FT spectra of ΔR_{eo} of GaP/Si(001) samples I and II. Sample II features mainly two oscillatory modes: the optical phonon of Si substrate at 15.6 THz and the LO phonon of GaP at 12 THz. The GaP LO phonon

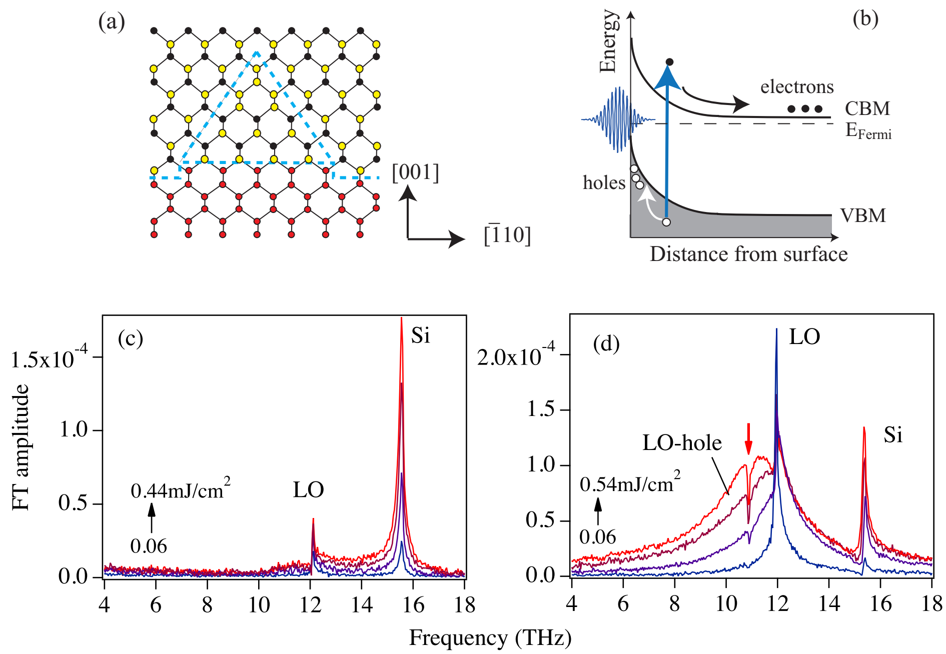

Fig. 1. (a) Atomic model for APDs on P-P exclusive {111} planes. (b) Schematic energy diagram of an n-doped semiconductor surface. (c,d) FT spectra of anisotropic reflectivity changes of GaP/Si(001) samples: sample II without APD (c) and sample I with APDs (d).

is smaller in amplitude than Si phonon. Sample I, by contrast, exhibits an intense LO phonon peak. In addition, a prominent broad peak appears, whose frequency downshifts with increasing pump density. This mode is observed also for n-type GaP(001) wafer and assigned as the coherent LO phonon coupled with photoexcited hole plasma [3]. For n-type GaP(001) surface, photoexcited electrons drift swiftly into the bulk whereas holes accumulate at the surface due to the upward band bending toward the surface, as shown in Fig. 1(b). This ultrafast current in the surface normal direction gives the driving force for launching the coherent LO phonons. In the present study, the efficient generation of the coherent phonons and their coupling with photoexcited holes indicates that APDs within the GaP film induces a similar upward band bending toward the surface, even if the film is nominally undoped.

Sample I also features an oscillation at 11 THz, which appears as a sharp dip against the broad LO-hole peak in the FT spectra, as shown with a red arrow in Fig. 1(d). The frequency of 11 THz coincide with that of the TO phonon of GaP. However, the generation and detection of the bulk TO phonon from a zinc-blende crystal via Raman scattering is dipole-forbidden in the present back-reflection geometry. Indeed, no TO signal is detected from GaP(001) in the same configuration [3]. We therefore attribute the 11-THz mode to the symmetry breaking of the GaP lattice, either at the GaP/Si interface or at APBs.

4. Conclusion

Plasmon-phonon dynamics of GaP/Si(001) is investigated by photodoping with near ultraviolet optical pulses. The LO phonons and the LO-hole coupled mode are significantly enhanced in their amplitudes by the presence of APDs, indicating a steep band bending within the GaP film. A distinct oscillation at a TO phonon frequency, possibly due to the lattice symmetry breaking, is also observed. Our results suggest that APDs can significantly affect the electronic states within the nanometer-thin GaP films grown on exact Si(001) substrate. We thus demonstrate the applicability of the coherent phonon spectroscopy to non-destructively monitor the carrier-phonon dynamics at a buried interface.

References

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