Laser-induced coherent GHz surface acoustic waves in cleaved superlattices

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Background, Motivation and Objective – Coherent GHz surface acoustic waves (SAWs) hold potential usefulness in various fields including nanometrology, nanoimaging, sensoring and filters. The hypersonic frequency enables the fundamental investigations and applications with the nanometer spatial resolution and the picosecond temporal resolution. Experimentally, up to 100 GHz SAWs can be manipulated by using ultrafast lasers on the metallic gratings deposited on a substrate [1]. The nanometer period of the light-absorbing grating determines the spatial period of SAWs. Reaching higher frequency is limited by nanopatterning techniques. In theory we have earlier proposed to engineer unconventional cleaved bulk superlattices (SLs) for SAW transducers [2]. In this way, SLs epitaxially-grown with atomic precision and cleaved along the growth direction provide access to SAWs above 100 GHz. Here, we report the experimental realization of this methodology.

Methods – Ultrafast pump-probe laser experiments with a wide range of excitation/detection wavelength combinations are conducted to monitor SAWs. Semiconductor SLs composed of $Al_xGa_{1-x}As/Al_yGa_{1-y}As$, with different x/y compositions and individual widths, serve as the opto-acoustic (generation) and acousto-optic (detection) transducers. The laser beams are at normal incidence to the cleaved surface with the periodic nanostructure (Fig. 1(a)). For monitoring and identifying the $k \cong 0$ SAW modes, the configuration of the coincident pump and probe lights on SL is employed and the dispersion relation of the SLs with reduced wavevector along the periodicity axis is calculated by finite element methods. By moving the coincident laser beams to approach the SL edge, we search for the evidence of SAW emission from excitation region to outside the SL in the diminishing lifetime of SAWs. Separating the pump and the probe lights spatially enables us to track the propagation of the SAW packet (Fig. 1(b)). The SAW packet is extracted numerically by a band-pass filter from the time-domain reflectivity signal and its envelope is subsequently fitted based on its theoretical diffusive/ballistic propagation modelling.

Results/Discussions – We have optically monitored the folded SAWs and skimming longitudinal and transverse modes at $k \cong 0$. In the SLs with a period of ~70 nm and ~20 nm, first-order Rayleigh modes with the frequencies of ~40 GHz (Figs. 1(c)-(e)) and ~130 GHz are monitored, respectively. Theoretically, the ratio of the imaginary and the real parts of the Rayleigh mode frequency is proportional to the squared weak acoustical contrast (impedance ratio), indicating that the attenuation of the Rayleigh mode is small, which was confirmed by the numerical modelling. We estimated that the width (Δq) of monitored SAW k-spectrum (controlled by laser focusing) is comparable with the width (Δk) of the parabolic part of SAW dispersion relation in GaAs/AlAs SL (Fig. 1(f)), which means that the diffusive evolution of the SAW packet is dominant. Our experimental observations in these SLs are well fitted by the analytical theory of SAWs diffusion (Fig. 1(g)). By tailoring the composition of Al in the individual layers it was possible to reach in the $Al_{0.4}Ga_{0.6}As/Al_{0.2}Ga_{0.8}As$ SL such reduced acoustic contrast that the width (Δk) of the parabolic part of the dispersion relation is negligible compared to that (Δq) of the photo-excited k-spectrum of SAWs (Fig. 1(h)). Our analytical fittings for the detected SAW packets propagating between two such SLs separated by the GaAs substrate confirm their ballistic propagation (Fig. 1(i)).

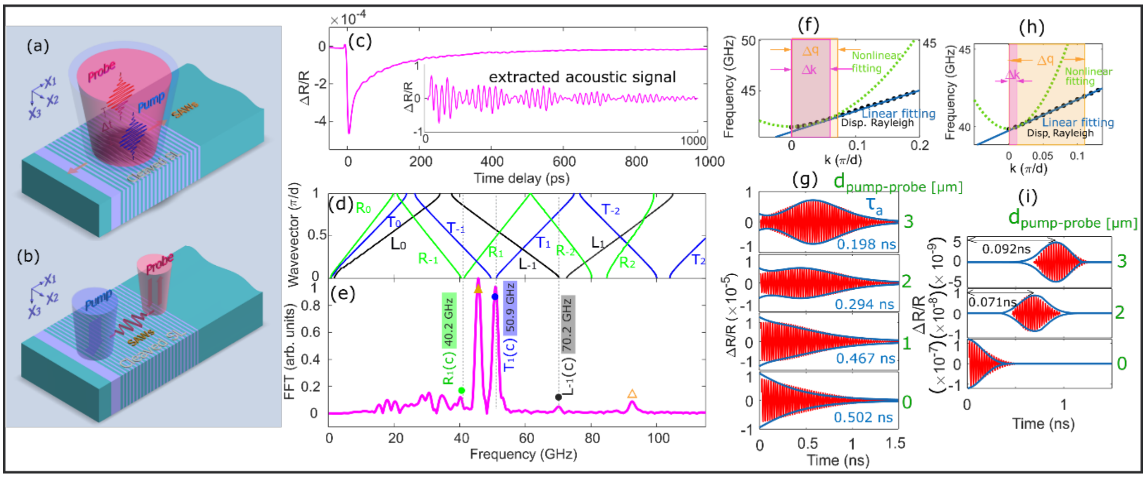

Fig. 1. (a)-(b): Illustration of pump-probe experiments in cleaved SLs. In the 71 nm-period GaAs/AlAs SL: **(c)** measured time-domain signal, **(d)** SAWs dispersion curves, **(e)** acoustic spectrum, **(f)** width of the parabolic part of SAW dispersion (Δk) vs. width of the photo-excited k-spectrum of SAWs (Δq), **(g)** filtered first-order zone-center Rayleigh SAW packets with their diffusive propagation fitting. In the $Al_{0.4}Ga_{0.6}As/Al_{0.2}Ga_{0.8}As$ SL: **(h)** width of the parabolic part of SAW dispersion (Δk) vs. width of the photo-excited k-spectrum of SAWs (Δq), **(i)** filtered first-order zone-center Rayleigh SAW packets with their ballistic propagation fitting.

Conclusions – We have experimentally proved that monitoring SAWs on the cleaved SLs by femtosecond lasers can extend their frequency range to above 100 GHz and decrease their localization depth close to single-digit nanometers. Our progress on SAWs monitoring will pave the way to their advanced applications in fundamental research, materials characterization, sensing, and information and communication technologies.

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