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Superlattice ultrasonic generation

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Abstract. We report the first experimental evidence for the resonant excitation of coherent high-frequency acoustic phonons in semiconducting doping superstructures by far-infrared laser radiation. After a grating-coupled delta-doped silicon doping superlattice is illuminated with $\sim 1 \text{ kW/mm}^2$ nanosecond-pulsed 246 GHz laser radiation, a delayed nanosecond pulse is detected by a superconducting bolometer at a time corresponding to the appropriate time-of-flight for ballistic longitudinal acoustic phonons across the (100) silicon substrate. The absorbed phonon power density in the microbolometer is observed to be $\sim 10 \text{ }\mu\text{W/mm}^2$, in agreement with theory. The phonon pulse duration also matches the laser pulse duration. The absence of any delayed transverse acoustic phonon signal by the superconducting bolometer is particularly striking and implies there is little or no incoherent phonon generation occurring in the process.

1. Introduction

Coherent phonons in a variety of materials, including metal films, bulk semiconductors and semiconductor heterostructures, have been studied for some time now using ultrafast pulsed lasers for their generation and detection [1]. Here, we investigate a different approach for coherent phonon generation, that of the direct electromagnetic generation of coherent high-frequency monochromatic acoustic phonons in silicon doping superlattices (DSL) by high peak-power, nanosecond-pulsed far-infrared (FIR) laser radiation. This approach has the potential to produce intense nanosecond pulses of high-frequency narrow-bandwidth coherent acoustic phonons of the desired polarization, with reasonable conversion efficiency, and without concomitant electronic or lattice heating.

2. Theory

A number of authors [2,3,4,5] have discussed the possibility of using FIR laser radiation to excite ultrasonic acoustic waves in superlattices in the frequency range 0.1-1 THz, although to date, there has been no experimental confirmation. A *nipi* doping superlattice consists of a periodic variation in the dopant in an otherwise homogeneous semiconductor with resulting layers of spatially separated and periodic space charge. The sinusoidally-varying electric field of incident far-infrared laser radiation will transfer to the crystal momenta of opposite directions in the alternating layers. If the superlattice period is chosen to match the acoustic wavelength, the resulting time-varying momenta in the crystal

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will induce a resonant acoustic wave of the same frequency as the electric field. In this case, the fundamental frequency of excitation of the generated phonons is simply given by $f=s/d$, where s and d are the phase velocity for phonons and the superlattice period, respectively (an optical phonon mode in the zone-folded scheme). In the case of the DSL fabricated upon the same type of crystal substrate there will be no reflection at the DSL/substrate interface and the wave generated in the DSL will propagate through the substrate.

Longitudinal (LA) or transverse (TA) acoustic phonons couple to electric fields normal or parallel to the DSL layers, respectively. The conversion efficiency ξ is defined as the ratio of the generated acoustic energy to the energy of the incident electromagnetic wave and is given by equation (1) (cgs units) below, where a is the host lattice constant (assumed simple cubic lattice), $n_D^{(2)}$ is the two-dimensional doping concentration, κ_0 is the dielectric constant, M is the atomic mass, d is the superlattice period, c is the speed of light, s is the phonon phase velocity, N is the number of superlattice periods, and $r \equiv (d/a)$, is the enlarged unit cell:

$$\xi \cong \left[\frac{(4\pi e^2 a^2 (n_D^{(2)})^2 (adN^2))}{(\kappa_0 Mdr)(cs\sqrt{\kappa_0})} \right] \quad (1)$$

3. Experiment

We have used a delta-doped silicon DSL [6,7] consisting of 30 periods, fabricated upon a (100) float zone silicon substrate, with a period of length $d = 34.5$ nm, and with individual layers having a two-dimensional doping concentration $n_D^{(2)} = 8.5 \times 10^{12}$ cm⁻². The conversion efficiency ξ of this DSL is 9.6×10^{-9} . The period was chosen to match the LA phonon wavelength in silicon at a frequency (245.5 GHz) corresponding to a particularly strong FIR laser line (1.22 mm) produced by a ¹³CH₃F gain medium.

We have used a small-period metallic grating coupler [8] on top of the DSL. Undesirable bulk broadband phonon generation might be expected in the absence of such a grating-coupling scheme, as a result of both multi-phonon- and defect-induced- absorption in the substrate. The grating-coupler also serves to protect the sensitive superconducting bolometer detector from direct exposure to the intense FIR laser radiation, i.e., heat pulse generation in bolometers exposed to intense FIR laser pulses has been observed previously. The grating coupler converts normally incident plane wave radiation, into an evanescent surface wave with a large electric field component perpendicular to the interface for efficient LA phonon generation. We have used a grating period of ~ 10 μ m, resulting in a decay length of ~ 1.6 μ m, somewhat larger than the thickness of our DSLs. Niobium is used as the grating material because of its small surface resistance below its superconducting transition temperature.

We have previously developed [9] a cavity-dumped optically-pumped molecular-gas FIR laser resonator, and modified it for use at 1.22 mm as a source of intense \sim nanosecond pulses of p-polarized FIR laser radiation for these experiments. We cavity-dump the circulating resonator FIR radiation through the use of an optically-switched intra-cavity intrinsic silicon wafer, oriented at the Brewster angle to the circulating p-polarized far-infrared radiation, through the absorption of above-bandgap radiation. The risetime of the cavity-dumped output pulse is on the order of a nanosecond and the pulsewidth corresponds to the roundtrip time of the circulating FIR – 6 ns. Recent improvements to the FIR laser have included: (1) an in-situ mode-matching Newtonian telescope, employing custom TPX lenses, to couple the output into a 3 m long 246 GHz corrugated waveguide for beam transport to the sample access window of the floor-mounted liquid helium cryostat and, (2) a recycling cryogenic absorption pump for the isotopic methyl fluoride gain medium. After the 246 GHz laser radiation propagates through our corrugated waveguide, we routinely obtain power levels at the cryostat access window of 5 kW in 6 ns pulses, at a pulse repetition rate of 10 pulses per second. The DSL sample is installed at the end of an insertable sample rod and is enclosed in a split-cylinder metal-coated ‘rapid-

prototyping' polymer jig that also holds a hyper-hemispherical high-purity silicon lens in contact with the grating-coupler/DSL front sample surface. The jig also shields the bolometer from scattered FIR radiation. The focused FIR laser power density at the surface of the grating-coupler/DSL is estimated to be $\sim 1 \text{ kW/mm}^2$ in a beamwaist of 3 mm.

The DSL sample assembly (rod and jig) is immersed in low-temperature liquid helium in a cryostat equipped with optical access. The temperature is established by pumping on the helium vapour through a precision computer-controlled butterfly valve with a vacuum pump. The temperature is typically held near 1.750 K (approximately 1/3 up the R-T curve for the superconducting bolometer detector) with a stability of 0.1 mK. Any resonantly excited phonons by pulsed FIR laser radiation are detected on the rear sample face (substrate thickness 0.5 mm) by a superconducting granular aluminium/palladium bilayer microbolometer operating in a constant bias-current mode [10]. The active region of our 100 nm thick granular aluminium bolometer is $10 \mu\text{m} \times 20 \mu\text{m}$ and is capped with a 5 nm thick palladium layer. We pattern both the niobium grating-coupler and microbolometer using image-reversal optical lithography, dual-target dc-magnetron sputtering, and liftoff. When biased at 20 μA and near 1.75 K, our bolometer has a bare time constant (C/G) of 2.9 ns and a calculated responsivity \mathcal{R} , at 50 MHz, of 9.8 kV/W. (50 MHz is the bandwidth associated with a 6 ns phonon pulse.) Electrical contact is made to the bolometer with an MMCX microminiature coaxial jack that is integrated into the rear half of the split-cylinder sample jig. A 1 GHz bias tee passes the battery-powered dc-bias current through to the bolometer while allowing the ac-coupled bolometer output to be passed to a 1 GHz preamplifier (voltage gain 35 dB). It was necessary to enclose the cryostat and bolometer electronics in a copper Faraday cage in order to shield the experiment from intense electromagnetic noise generated by the pulsed TEA CO₂ pump laser and the pulsed frequency-doubled YAG laser (the latter induces the cavity-dumping of the FIR laser resonator).

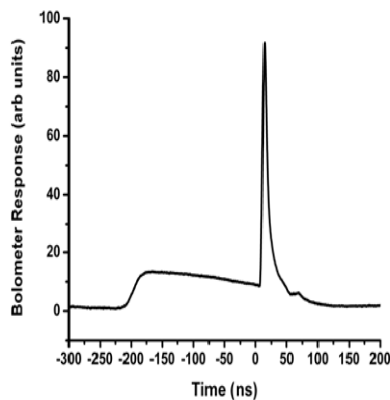


Figure 1. Bolometer response (arbitrary units) 25 ns/div

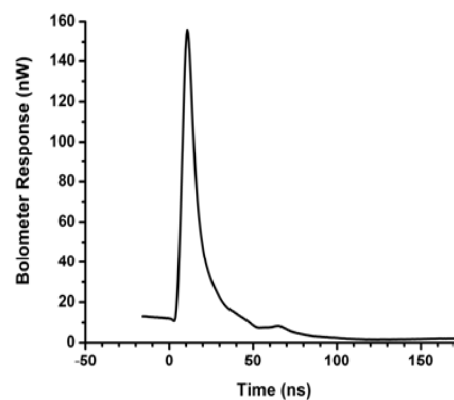


Figure 2. Bolometer response (nW) 10 ns/div

Figure 1 above shows the response of the bolometer. We first observe (beginning near -225 ns) pulsed FIR laser radiation leaking through the 500 nm thick superconducting niobium grating coupler (skin depth $\sim 39 \text{ nm}$). Next, one observes the onset of the large cavity-dumped FIR pulse near 0 ns (the cavity-dumped pulse has saturated the bolometer; hence, the pulse is seen to be larger in time than 6 ns, the observed FIR pulsewidth in earlier experiments). Finally, one observes a delayed ($\sim 65 \text{ ns}$) smaller pulse corresponding to the arrival for ballistic LA phonons that have traversed the 0.58 mm thick (100) Si substrate. Figure 2 displays the bolometer response at higher time resolution; there is no evidence of either transverse ballistic or diffusive acoustic phonons. The absence of a TA phonon signal is to be compared to an earlier heat pulse experiment [10] on identical DSL samples; in that case 0.5 μJ , 532 nm, 1 ns pulsed mini-YAG laser radiation was focused on the Nb grating-coupler/DSL to a beam waist of 50 μm and a similar (identical geometry and bias conditions) superconducting granular

aluminum/Pd bolometer was used as the detector. In the latter case, both LA and larger (due to phonon focusing) TA phonon signals were clearly observed at the appropriate delays relative to the initial pulse of scattered laser light reaching the bolometer. We take this to be evidence that there is very little incoherent heat pulse generation observed in our new results. It is also noteworthy that the absorbed power at the bolometer in the case of figure 2 also matches closely the coherent power predicted by Ruden and Dohler [2] for our 200 μm^2 active area microbolometer, i.e., ~ 2 nW.

4. Conclusions

We provide evidence for the first experimental demonstration of the coherent generation of acoustic phonons in doping superlattices by pulsed FIR laser radiation. The absorbed phonon power density in the microbolometer is estimated to be ~ 10 $\mu\text{W}/\text{mm}^2$, in agreement with theory [2]. The observed phonon pulse duration (~ 5 ns) in figure 2 matches the FIR laser pulse duration. The absence of any larger and delayed transverse acoustic phonon signal by the superconducting bolometer is particularly striking. These observations taken together provide strong evidence that coherent zone-folded longitudinal acoustic phonons can be generated in a silicon doping superlattice through the resonant absorption of grating-coupled pulsed far-infrared laser radiation, and with negligible associated electronic or lattice heating. In the near future, we plan to increase the thickness of the niobium grating-coupler so as to reduce the FIR laser radiation leakage and thereby allow for Si:B phonon spectroscopy, to use larger bolometers to intercept a larger phonon flux, and to investigate the use of new DSL samples with significantly larger number of periods. We hope to develop a THz cryogenic acoustic microscope [11] with ~ 1 nm lateral resolution, using the superlattice as a novel high-frequency transducer. We acknowledge the support of the United States National Science Foundation through an ECCS grant 0622060.

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