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Evidence of Longitudinal Acoustic Phonon Generation in Si Doping Superlattices by Ge Prism-Coupled THz Laser Radiation

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Abstract. We report on the direct excitation of 246 GHz longitudinal acoustic phonons in silicon doping superlattices by the resonant absorption of nanosecond-pulsed far-infrared laser radiation of the same frequency. A longitudinally polarized evanescent laser light field is coupled to the superlattice through a germanium prism providing total internal reflection at the superlattice interface. The ballistic phonon signal is detected by a superconducting aluminum bolometer. The sample is immersed in low-temperature liquid helium.

1. Introduction

The optical generation of coherent, monochromatic acoustic phonons has been a long-standing goal in solid-state physics. It is has been demonstrated that it is possible to generate coherent pulses of longitudinal acoustic (LA) phonons in a gallium arsenide/aluminium arsenide compositional superlattice by femtosecond laser excitation when the excitation energy matches the E1-HH1 transition in the superlattice [1]. This excitation mechanism used to generate the coherent longitudinal acoustic pulse undoubtedly also generates a burst of incoherent phonons by carrier relaxation in the gallium arsenide. Alternatively, the possibility of direct action of the electric field of a FIR light wave on the layers of bound space charge to resonantly generate single polarization sound, was discussed in the context of doped superlattices, as early as 1983 [2]. In this vein, Ruden *et al*. [3] have studied the effects on the lattice dynamical properties of an otherwise homogeneous semiconductor, stemming from impurity charges associated with a microstructured one-dimensional periodic *n* and *p*-doping sequence, a so-called *nipi* doping superlattice (DSL). The phonon dispersion relation is nearly unchanged, as one might expect from a concentration of 10^{-3} impurity atoms or even less. The periodic space charge resulting from the doping superstructure, however, is the origin of a unique feature: LA or transverse acoustic (TA) phonons, with wavevectors corresponding to odd multiples of the smallest reciprocal superlattice vector, may be directly excited by electromagnetic fields of the corresponding frequency with reasonable conversion efficiency. The fundamental resonant frequency *f* for the generated phonons is given by $f=s/d$, where *s* and *d* are the phase velocity for LA phonons and the superlattice period, respectively.

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2. Theory

LA acoustic phonons couple to electric fields normal to the DSL layers. 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:

$$\xi = \left[\frac{4\pi d (ea^2 n_D^{(2)} N)^2}{\kappa_0^{3/2} Mrcs} \right] \tag{1}$$

The upper limit to the two-dimensional (donor or acceptor) doping concentration is determined by the condition that there be an effective bandgap. The limiting doping concentration follows from equations (1) and (8) in Ruden [3], and is given in equation (2) below:

$$n_D^{(2)} = \frac{2E_g \kappa_0}{\pi de^2} \tag{2}$$

where E_g is the host bandgap. At this doping level, the thin sheets of acceptors and donors are degenerate and there will be no carrier freeze out at liquid helium temperatures. In its ground state, the sample thus consists of alternately positively and negatively charged sheets of ions. Care must be taken to insure that the sample has a closely balanced dopant concentration.

3. Superlattice and THz laser source

We use a delta-doped DSL consisting of 30 periods, grown on a [100] float zone high-resistivity 0.61 mm thick silicon substrate. The superlattice layers have a period $d = 34.5$ nm and the individual layers have a two-dimensional doping concentration $n_D^{(2)} = 8.5 \times 10^{12}$ cm^{-2}. From equation (1), the conversion efficiency of this DSL is $\xi = 9.6 \times 10^{-9}$. The period was chosen to match the LA phonon wavelength in silicon at a frequency (246 GHz) corresponding to a particularly strong FIR laser line (1.22 mm) produced with a $^{13}CH_3F$ gain medium. An experimental requirement was the development of a nanosecond pulsed kilowatt FIR laser source - kilowatt power is required for the relatively small conversion efficiency of electromagnetic power into acoustic power, and nanosecond pulses are required to resolve the LA and TA phonon time-of-flights across the thin substrates typically used for MBE-based DLS growth. The author has previously described his development of a cavity-dumped multi-kilowatt source of nanosecond-pulsed FIR laser radiation by optically-switching a Brewster-angle mounted silicon wafer placed within a conventional pulsed optically-pumped molecular gas laser [4]. In this experiment, radiation from the 9P32 TEA CO$_2$ laser line, containing 300 mJ in a 300 ns pulse width at 10 prf, is hole-coupled into the FIR laser resonator. The FIR resonator is a near-concentric design with stability parameters g_1 and g_2 equal to -0.12 and -0.52, respectively. The smallest beam waist w_0 is *12.6 mm* at the silicon wafer. The cavity-dumped FIR laser radiation output is then mode-matched, using TPX lenses, into a 246 GHz overmoded H11 segmented corrugated waveguide of inner diameter 22 mm and length 3 m. A Teflon lens at the end of the waveguide then focuses the radiation to a beam diameter of 4 mm upon at the Ge prism-coupled DSL. The typical FIR laser pulse width is 6-7 ns and corresponds to the cavity-dumping time for the round-trip distance (2 m) between the silicon wafer and one end resonator mirror. The average pulse energy is measured with a *Scientech* calorimeter and corresponds to a peak power of ~10 kW. The Q-switched YAG laser pulse may be delayed relative to the TEA CO$_2$ pump pulse by a delay generator such that a longer delay results in decreased FIR pulsed power.

4. Experiment
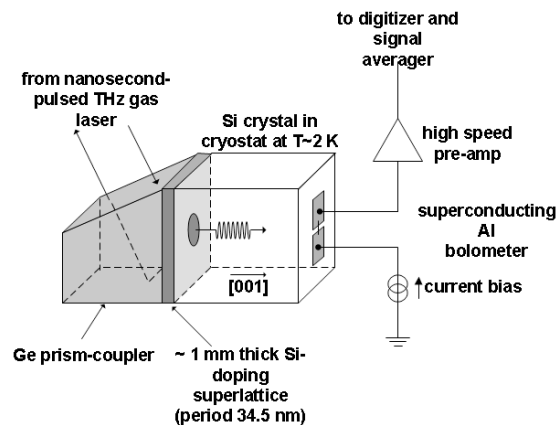
Figure 1. Schematic of experimental arrangement.

The experimental arrangement is shown above in figure 1. 246 GHz p-polarized laser radiation is transported via the corrugated waveguide and focused through a Teflon lens, enters through a crystal quartz window of a *Janis Research* 8-CNDT immersion cryostat with optical access and illuminates a Ge prism in contact with the DSL. The DSL/Si substrate has a frontal area of 5 mm x 7 mm and is 0.61 mm thick. The THz laser radiation is incident upon a truncated 30-60-90 degree high-purity Ge prism. The prism base is of dimension 9.2 mm x 6.1 mm. The incident angle of 60 degrees at the Ge/Si DSL interface exceeds the critical angle (58.4 degrees) and the FIR light is totally internally reflected. The resulting evanescent field within the superlattice is longitudinally-polarized normal to the superlattice layers with a decay length at this frequency of 0.35 mm. Phonon detection is made with a superconducting bilayer granular aluminum/palladium bolometer operating in a constant-current mode. We fabricate the bolometers using a bilayer lift-off recipe with sputtering, as described previously [5]. The bolometer is of dimension 10 x 20 μm^2 and 100 nm thick. The bolometer responsivity is calculated from characterization to be 1.7 kV/W. Typical bias temperatures and currents are 1.8 K and 20 μA, respectively. Temperature control is maintained by pumping on the vapor above the liquid helium bath through an *MKS 653B* throttle valve with an *Oerlikon Sogevac SV-100B* vacuum pump. The throttle valve aperture is adjusted under *LabView* control with an MKS 600 pressure controller with feedback from an *MKS 626* pressure sensor. Temperature stability is better than 0.2 mK near 1.8 K.

5. Results and Discussion

Figure 2 shows first results of the presence of the expected coherent acoustic phonon signal. The amplified bolometer response (in mV) is plotted versus time (in nsec). Three traces are shown, corresponding to different levels of bolometer bias current. The bolometer signal also contains a lower-frequency noise component due to the pickup of RFI from the TEA CO_2 laser that is manifested here by a sloped baseline that is also a function of bias current. The cavity-dumping time delay also has been increased from the optimal delay in order to minimize the RFI noise signal. The first pulse observed, occurring near 280 ns in figure 1, is assumed to be the decaying evanescent THz light field that leaks into the substrate and illuminates the bolometer. It is coincident with the YAG Q-switching 532 nm light pulse (not shown). The second pulse, arriving ~50 ns later, is assumed to be the coherent longitudinal acoustic phonon pulse traveling ballistically across the 0.61 mm thick substrate. If one uses the LA sound speed in [100] silicon of 8450 m/s obtained from low-frequency acoustic velocity measurements [6], the expected arrival time would be considerably longer however, namely, 72 ns. The shorter time-of-flight of the measured phonon pulse could result from the elastic constants at 246 GHz being substantially different, or from a stiffening of the silicon due to stress caused by the

phonons. The latter would then probably be related to solitons [7]. We also note the absence of any observed delayed and larger TA phonon pulse as occurs with heat pulse production along [100] Si.
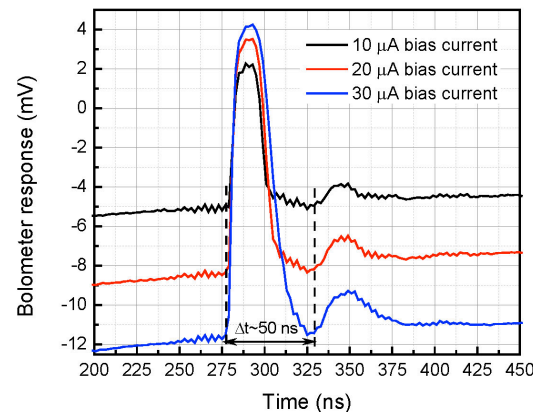
Figure 2. Bolometer signals that show the presence of a secondary pulse (near 325 ns) presumed to be due to coherent phonons arriving at a delay of 50 ns from the earlier incident laser light pulse (near 275 ns).

6. Conclusions and Future Work

We have presented evidence for coherent acoustic phonon generation by the resonant absorption of Ge prism-coupled nanosecond-pulsed 246 GHz FIR laser radiation in silicon delta-doped doping superlattices. The technique produces *single polarization* acoustic phonons with negligible associated broadband heat pulse production. The time-of-flight for the ballistic phonon pulse observed in [100] Si is significantly smaller than that expected for lower-frequency sound speeds. We will soon use two metal-mesh polarizers to rotate the polarization of the incident FIR laser radiation for an in-plane electric field polarization to see if the phonon signal is reduced or extinguished as expected. Future plans are to: (1) include the use of a faster (30-nm thick) bolometer to investigate the presence of acoustic solitons on the front edge of the phonon signal, (2) conduct similar investigations at 1.04 THz, (3) use Si:B piezophonon spectroscopy [8] to verify the monochromaticity of the phonon signal and (4) use a stack of DLS's each with separate resonant frequencies to realize a discretely tunable coherent THz acoustic phonon source.

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