

## Ultrahigh-frequency surface acoustic waves for finite wave-vector spectroscopy of two-dimensional electrons

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Ultrahigh-frequency (up to 24 GHz) surface acoustic waves were excited with short-period interdigital transducers and detected in GaAs/AlGaAs quantum wells with an optical scheme. We demonstrate that the transducers can be driven in a contactless fashion. Sets of two transducers permitted the coherent emission of surface acoustic waves and the creation of standing waves due to interference. The methods described offer bright prospects for finite wave-vector spectroscopy of two-dimensional electrons in a noninvasive way up to wave numbers of  $10^6 \text{ cm}^{-1}$ . © 2004 American Institute of Physics. [DOI: 10.1063/1.1815068]

The properties of both ground and excited states of a two-dimensional electron system (2DES) exposed to a perpendicular magnetic field are often governed by Coulomb interactions. Fractional quantum Hall states,<sup>1</sup> composite fermions,<sup>2</sup> and the Wigner crystal<sup>3</sup> are well known examples of strongly correlated ground states. Electron–electron interactions also manifest in the dispersion of excitations, such as magnetoplasmons<sup>4</sup> and spin excitons (or spin waves).<sup>5,6</sup> According to Kohn's<sup>7</sup> theorem, homogenous electromagnetic radiation incident on any translationally invariant system can only couple to the center-of-mass coordinate and is unable to excite internal degrees of freedom associated with the Coulomb interaction. Hence, phenomena originating from such interactions remain hidden for optical transitions with zero-transferred momentum. An elegant way to overcome this limitation for optical studies consists in the creation of a periodic density modulation or some other means to modulate the dielectric constant, so that incident radiation is perceived as inhomogeneous by the two-dimensional (2D) electrons. Optical transitions at the nonzero wave vector defined by the modulation period become observable and may contain information on Coulomb correlations.

With metallic gratings deposited on top of the 2DES,<sup>7,8</sup> electron–electron interaction contributions to the cyclotron resonance have been established and the magnetoplasmon dispersion has been measured.<sup>9</sup> However, these gratings cover the area exposed to optical radiation and restrict the minimum modulation period as the incident radiation should be allowed to penetrate. As a result, this technique is only applicable for momenta  $K < 10^5 \text{ cm}^{-1}$ . Interactions governing the dispersion of many collective excitations in the 2DES start to dominate at wavelengths comparable to the mean interparticle distance. Hence, the most interesting range of momenta corresponds to  $K > 10^6 \text{ cm}^{-1}$ , but is inaccessible in

metallic grating-based experiments. In this letter, we propose a technique based on the generation of ultrahigh-frequency (up to 24 GHz) surface acoustic waves (SAWs), which enables finite wave-vector spectroscopy up to  $10^6 \text{ cm}^{-1}$ .

SAWs propagating on a piezoelectric GaAs substrate are accompanied by an electric field penetrating down to the 2DES. It may serve as a slowly travelling (at the speed of sound) weak periodical potential superimposed on the electronic system. If two coherent sources of SAWs are simultaneously excited, a standing SAW potential can be obtained. This approach to break translational invariance has many advantages over metallic gratings: (a) It is noninvasive, since the transducers generating the SAWs are patterned far away from the active area. A metallic layer does not mask part of the 2D electrons underneath, which enhances the signal in optical experiments. Moreover, metal in the active device area screens the Coulomb interaction and curtails its range to the distance separating the 2D electrons from the surface. Surface metal thereby potentially modifies the physics under study. (b) The modulation amplitude is tunable by applying different power levels to the transducers. (c) The modulation period is defined by the SAW wavelength and can in principle be very small. SAWs have been exploited previously for investigating 2D electrons,<sup>10,11</sup> however, only for transport studies of electrons and composite fermions.<sup>12</sup> There, interdigital transducers were applied both for excitation and for detection of SAWs. The spatial period of the transducer determines the frequency and wavelength of the SAW. Typical frequencies were 1–3 GHz and frequencies up to 8 GHz have been reported on GaAs in the literature.<sup>13</sup> In order to achieve our goal, SAWs with frequencies above 20 GHz are needed. Apart from the nontrivial fabrication of small period interdigital transducers, there is the even more difficult task to detect such waves. The conventional electronic approach using a second transducer as a detecting element fails rapidly with increasing frequency. Here, we report on an optical detection approach, which provides much larger sensitivities at frequencies exceeding 10 GHz as it avoids the inefficient conversion to a high-frequency electrical signal and the losses associated with propagating this signal on coaxial

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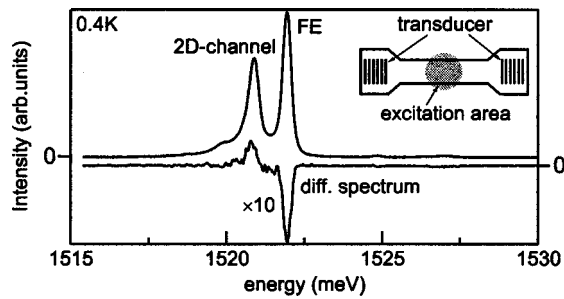


FIG. 1. Top: Luminescence spectrum measured at a density of  $3 \times 10^9 \text{ cm}^{-2}$  and 0.4 K. Bottom: Differential luminescence spectrum ( $\times 10$ ) measured at the resonance frequency 11.97 GHz of the transducer with a period of 240 nm. The excitation power for the transducer was 0.1 mW. The inset shows a schematic of the device mesa with the transducers.

lines before amplification at room temperature. Our method relies instead on SAW-induced modifications in the luminescence spectrum of 2D electrons.<sup>14,15</sup>

Undoped GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures containing a 30 nm wide quantum well served our studies. The electron density and mobility were measured from the position and the linewidth of the dimensional magnetoplasma resonance.<sup>16</sup> The density was in the range of  $n_s = 2\text{--}5 \times 10^9 \text{ cm}^{-2}$  and the mobility was about  $\mu = 0.5 \times 10^6 \text{ cm}^2/\text{V s}$ . Several identical mesas of the shape depicted in the inset to Fig. 1, were produced. Each mesa is composed of a narrow active region, 1 mm in length and 0.1 mm in width. The mesa terminates on either side in a wider section, where two identical metallic interdigital transducers with 100 fingers were patterned with periodicities  $p$  varying from 320 to 160 nm. SAW resonances were detected with an optical detection scheme. Luminescence spectra were recorded with and without SAW excitation and subsequently subtracted to build the differential spectrum. The amplitude of the SAW absorption is defined as the integral of the absolute value of this differential spectrum over the entire spectral range. The spectra were acquired with the help of a charge coupled device camera and a double-grating monochromator with a resolution of 0.03 meV. A stabilized semiconductor laser operating at 750 nm provided continuous-wave excitation at a power level of 0.1 mW distributed across the active device area. The excitation of SAWs proceeds by applying high-frequency signals to the transducers with coaxial lines and an HP-83711A generator (0.1–20 GHz).

In Fig. 1, the luminescence spectrum from the GaAs quantum well is plotted. It exhibits two lines. One line corresponds to the recombination of free excitons (marked as FE in Fig. 1), whereas the other originates from recombination of free 2D electrons with a density of  $3 \times 10^9 \text{ cm}^{-2}$ .<sup>16</sup> Despite the absence of intentional dopants, residual donors in the AlGaAs layers are responsible for the presence of a 2D-electron channel.<sup>16,17</sup> When applying 11.97 GHz to the transducer with a 240 nm period, a SAW is resonantly excited and a strong modification of the luminescence takes place. The excitonic line drops in intensity. Exciton polarization and electron-hole separation in the strong electric field of the SAWs<sup>14</sup> are held responsible for this drop. They favor recombination from the 2D channel instead. Figure 1 shows the corresponding differential spectrum. These modifications under SAW are typical for low-density systems, in which excitonic recombination normally dominates the spectrum.

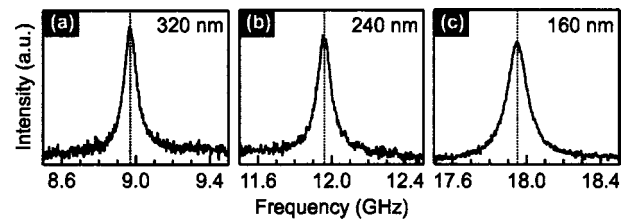


FIG. 2. Optically detected resonant excitation of SAWs measured at 0.4 K for interdigital transducers with different periods: 320 nm (a), 240 nm (b), and 160 nm (c).

To demonstrate the resonant character, Fig. 2(b) plots the dependence of the absorption amplitude (i.e., the integral of the absolute value of the differential spectrum) on the frequency applied to the transducer. A response occurs only in a very narrow frequency range from 11.9 to 12.1 GHz with a well-defined maximum at  $f_{\text{res}} = 11.97 \text{ GHz}$ . At this frequency, the wavelength  $\lambda_{\text{SAW}}$  of the excited SAW coincides exactly with the period of the transducer:  $\lambda_{\text{SAW}} = V_{\text{SAW}}/f_{\text{res}} = 240 \text{ nm}$ . Here,  $V_{\text{SAW}}$  is the propagation speed of the SAW in GaAs and equals  $2.87 \times 10^5 \text{ cm/s}$ . In Figs. 2(a) and 2(c), this experiment was repeated for transducers with 320 nm and 160 nm, respectively. Again, very sharp resonances were established when  $\lambda_{\text{SAW}} = p$ . The width of these resonances was approximately 0.1–0.2 GHz and follows from the number of fingers of which the transducers are composed.

For coherent excitation of two counterpropagating SAWs, a pair of transducers was taken at a distance  $L$  of 1.6 mm apart. The SAW excitation resonance appears at the same frequency, but a rapidly oscillating signal is superimposed on the envelope of the resonance as seen in Fig. 3. The inset of Fig. 3 shows an expanded view. The period of the oscillations  $\Delta f$  is approximately 1.7 MHz. We assert that these oscillations originate from the interference of the SAWs generated on opposite sides of the sample as their periodicity agrees quite well with the value obtained from  $\Delta f = V_{\text{SAW}}/L$ . Hence, with a pair of transducers, the 2D electrons in the active region can be subjected to a standing rather than a propagating wave.

We also explored a contactless approach to drive transducers. To this end, samples with unbonded transducers were placed in a hollow 16 mm microwave waveguide (WR62) in order to irradiate them with microwaves, polarized in the direction perpendicular to the transducer fingers, with the help of an Agilent 83650B generator covering frequencies up to 50 GHz. The sample is placed in the maximum of the microwave-electric field of the waveguide, which is short circuited at one end near the sample and contains a fiber in

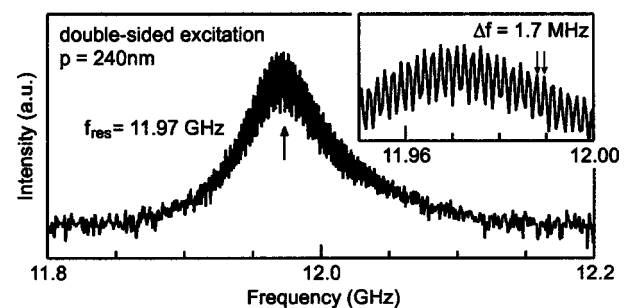


FIG. 3. Optically detected resonant coherent excitation of SAWs at 0.4 K for a pair of 240 nm transducers. The inset shows the interference pattern on an enlarged scale.

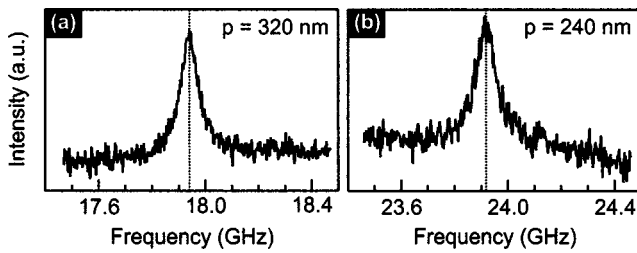


FIG. 4. Optically detected resonant excitation of SAWs at 0.4 K for “unbonded” transducers.

its center for optical excitation and collection of the luminescence signal. Typical values of microwave power inserted for contactless SAW excitation are 0.1–0.3 mW. A sweep of the incident microwave frequency across a wide range revealed a weak but narrow resonance at double the frequency of the transducer. Examples are shown in Fig. 4 for the 320 and 240 nm period transducers. Resonant excitation occurs at 17.95 GHz and 23.9 GHz, respectively. We were unable to detect such a resonance for the 160 nm period transducer with an expected resonance frequency at 36 GHz. This contactless approach to excite SAWs is far less efficient and demands nearly two orders of magnitude higher power levels. This presumably accounts for the absence of a resonance for the 160 nm period transducer at the power levels used. Despite this poor efficiency, the method offers the enormous advantage of producing SAWs at double the frequency. We attribute this frequency doubling to the following scenario: The uniform electric field of the microwave inserted into the waveguide is screened by the metallic fingers of the transducer. It results in a periodic spatial modulation of the electric field with a period equal to the distance between the nearest fingers  $p/2$  rather than the period  $p$  itself.

In conclusion, we developed a technique for the excitation and detection of ultrahigh-frequency SAWs up to at least 24 GHz. It opens up the possibility for finite wave-vector spectroscopy of 2D-electron systems in GaAs for momenta as large as  $10^6/\text{cm}$ .

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