Quantum Surface Acoustics

Propagating phonons coupled to an artificial atom
Martin V. Gustafsson, Thomas Aref, Anton Frisk Kockum, Maria K. Ekström, Göran Johansson, and Per Delsing, Science **346**, 207 (2014).

Surface acoustic wave devices on bulk ZnO crystals at low temperature
E. B. Magnusson, B. H. Williams, R. Manenti, M.-S. Nam, A. Nersisyan, M. J. Peterer, A. Ardavan, and P. J. Leek, Applied Physics Letters **106**, 063509 (2015).

Recommended with a Commentary by David DiVincenzo,
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Quantized mechanical vibrations, of nano-beams, -membranes, and -tubes, have become a deservedly popular set of tools in the quantum toolbox. In current work, another such tool has been recognized and analyzed: it is that most traditional of quantized mechanical vibrations in solid state physics, the crystal acoustic phonon. The emphasis is in fact on the manifestation of these excitations on piezoelectric crystal surfaces. Surface acoustic waves (SAWs) also have a decades-long history of application in quantum devices, but up to now the SAWs themselves were used only classically. Near-surface electrons can be made to surf on high-amplitude SAWs, leading to a metrological linkage between frequency and electric current, and to schemes to produce controlled collisions between electrons to enact quantum logic gates [1].

The wave equations of SAWs are complicated, but as a matter of principle their quantization goes along not very differently from the case of electromagnetic radiation. Thus, the quantum optics toolkit, developed originally for light and transposed with great success in recent years to the microwave regime, theoretically transfers without many surprises to the case of propagating phonons. Because the interaction is fundamentally electric, as mediated by the piezoelectricity, the situation at the model level is almost identical to quantum optics, and not like the situation in optomechanics where "radiation pressure" interactions are dominant. Recent papers [2, 3] have laid out the theoretical possibilities: cavity structures permit phononic resonant modes to Rabi-couple to qubits, high Q factors and strong coupling make quantum hybrid dynamics possible, phononic waveguiding makes possible entanglement at a distance as well as the generation of non-classical statistics of the phononic field. It is recognized that the slow propagation velocity of the phonons, compared to c, makes SAW resonators more compact than microwave ones, and makes it permissible to consider immediate-feedback protocols in quantum manipulations.

But these theoretical ideas are only timely because of the new experimental capabilities that are evident in the works of Gustafsson *et al.* and Magnusson *et al.*. The first of these exploits a very happy coincidence between the technology of SAWs and that of the transmon superconducting qubit. A thoroughly understood technique for launching SAWs, well established for the (100) crystal surface of GaAs in the work of [1] and long before, uses the so-called interdigital transducer (IDT), an array of long parallel electrodes to which ac voltages are applied. At the right frequency the line spacing matches the wavelength of the corresponding SAW, and efficient emission is possible. The transmon qubit, basically a Josephson junction shunted by a large capacitance, often gets its large capacitance with an interdigitated electrode structure. Thus, Gustafsson *et al.* use a second IDT, with some modifications, to function as the transmon capacitance, and puts it downstream of an IDT launcher (all aligned in the <011> direction, for strong piezoelectricity). The transmon "picks up" the phononic radio signal, down to the single-phonon level. The chosen center frequency of the antenna, around 5 GHz, is right around the "sweet spot" for transmon qubit operation. This gives every indication that the full set of qubit manipulations with cavity boson excitations should be possible.

Magnusson *et al.* is a more narrowly technological study (there are no qubits in this experiment), but the experiments in this paper show how the standard SAW toolkit, as practiced in the last decade or more in quantum-device experiments, can be dramatically improved by well-planned modifications. The IDT undergoes a metamorphosis, emerging here with no fewer than 1730 wires in the electrode array! This easily-fabricated extension becomes an excellent Bragg mirror for SAWs; making a simple 1D Fabry-Perot cavity with these mirrors, Q factors are measured in excess of 10^5 at 5 GHz. As the wire spacing is only modestly sub-micron at this frequency, it seems that one could make these mechanical resonators, presumably also with excellent Q, up to perhaps 50 GHz. No other mechanical resonator in the optomechanical toolbox has any chance of pushing up to such a high frequency. Magnusson *et al.* achieve this not in the established GaAs system, but in ZnO, a strong piezoelectric for which the achievement of high Q required some extra work; unintentional doping makes carrier losses significant, but these carriers are sufficiently frozen out at low temperature.

Some of the current theoretical plans [2] for a full set of capabilities for quantum-SAWs continue to assume the GaAs (100) surface as the preferred platform. But while GaAs is certainly the preferred host for qubits made possible by the two-dimensional electron gas, the kinematics of SAWs on the GaAs surface is far from ideal: the SAW propagating in the <011> direction (preferred because it exhibits the strongest piezoelectric polarization) is faster than the bulk TA phonon, so that any imperfection (disorder, or misalignment of the propagation direction) permits surface-bulk coupling, resulting in a finite lifetime for this SAW. The SAW in the <001> direction is slower than the bulk phonon in this direction, and so it stable, but has no piezoelectricity. For in-between propagation directions there is a complicated anticrossing between surface and bulk phonons. The upshot of this is that most propagation directions on GaAs are unsuitable for SAWs, and it would be unwise to envision a real "optics" on this surface (e.g., waveguides, focusing mirrors). All this was copiously documented and sorted out by 1970 [4], but it is not clear that this knowledge is fully accounted for in the current papers. Basal-plane ZnO, on the other hand, presents a very different picture. The surface acoustics, and the accompanying piezoelectric response, is perfectly isotropic on this hexagonal crystal face, and its surface waves are fully and robustly decoupled from the bulk waves, so that a full 2D optics can be expected here. (This was also completely known fifty years ago.) So, ZnO is ideal phononically and piezoelectrically, but unfortunately not electronically. We can anticipate a period when a more comprehensive material and device optimization is studied in this area. I am confident that the many lessons from our forefathers will all be quickly relearned, and then surpassed.

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[3] Thomas Aref, Per Delsing, Maria K. Ekstrom, Anton Frisk Kockum, Martin V. Gustafsson, Goran Johansson, Peter Leek, Einar Magnusson, and Riccardo Manenti, "Quantum Acoustics with Surface Acoustic Waves," arXiv:1506.01631.

[4] G. W. Farnell, "Properties of elastic surface waves," in *Physical Acoustics* vol. 6, eds. W. P. Mason and R. N. Thurston (Academic Press, New York, 1970), pp. 109-166.