Surface acoustic waves (SAWs) are mechanical wave modes confined to the surface of a material. In piezoelectric materials, a SAW is accompanied by an electric field and can thus be used for implementing electrical signal processing devices such as filters and oscillators, widely used in telecommunications. The response of a SAW device can also be very sensitive to external parameters such as temperature, pressure or mass loading of the surface, making them excellent candidates for a variety of sensors including biosensors, in which a functionalised surface binds to specific molecules.

SAWs are usually excited by means of a periodic AC electric field, requiring a piezoelectric material to be present to couple electric field to mechanical stress. Two configurations are commonly deployed: either the material (bulk) substrate is piezoelectric, or a thin layer of a piezoelectric material is deposited onto a non-piezoelectric substrate. To excite a SAW, an oscillating voltage of frequency $f_{\text{SAW}}$ is applied to an interdigital transducer (IDT) whose spacing determines the wavelength $\lambda_0$, such that $f_{\text{SAW}} \lambda_0 = v_{\text{SAW}}$. The SAW velocity $v_{\text{SAW}}$ is in the range $1-7$ km/s for commonly used single-crystal materials but can reach 12 km/s for layered systems. The IDT also works as a receiver, generating an oscillating voltage when a SAW of the right wavelength passes through it. A SAW reflector similar to an optical Bragg mirror may be implemented by a metal grating or grooves in the surface. Using these components, it is possible to construct delay lines (by spatially separating transmitting and receiving IDTs) and resonators (by enclosing an IDT between two reflectors).

ZnO is a relatively common material in SAW devices, but until now there have only been reports of its use as a thin layer piezoelectric transducer on top of a non-piezoelectric substrate such as sapphire, diamond or SiO$_2$/Si. Wafer scale bulk ZnO has recently become available, but even nominally pure material contains dopants that give rise to a non-zero room-temperature electrical conductivity. This conductivity damps SAWs efficiently, impeding the use of bulk ZnO in SAW devices.

Due in part to the development of bulk crystal growth, ZnO is receiving growing interest as a device material. Its electronic bandstructure, in particular its wide bandgap and large exciton binding energy, make it promising for optoelectronic applications such as ultraviolet light, and exciton based emitters. ZnO is also less susceptible to radiation damage than similar materials, making it a good candidate for space applications. ZnO has also recently been investigated as a possible material to be used in quantum information devices, due to the presence of long lifetime spin defect centres in the crystal.

In this paper we report measurements of SAW devices on the (0001) plane of high quality bulk wurtzite ZnO. We work at reduced temperatures to freeze out itinerant charge carriers, thereby decreasing the bulk electrical conductivity and the resultant SAW damping. We fabricate the devices using electron beam lithography and liftoff of a 5/50nm Ti/Al evaporated bilayer. We cool the devices down to a lowest temperature of 10 mK using a dilution refrigerator, and measure their frequency response using a vector network analyzer (VNA). We also perform two-contact electrical resistance measurements as a function of temperature on samples cut from the same ZnO wafer, using graphite paste for contacts, and a liquid $^4$He dewar dipstick fitted with a Cernox thermometer.

II. MEASUREMENTS

We measure delay lines with a short effective path length to measure temperature dependence at high temperatures, where we expect losses to be high. To observe low-temperature effects, we measure an under-coupled high quality resonator that is much more sensitive to any dissipation due to its long effective path length.
Figure 1. (a) Transmission spectrum of a delay line with 4 µm and 6 µm transducers. Multiple odd harmonics are seen. (b) Zoom of transmission spectrum at the fundamental mode \( f = 446 \) MHz of the delay line at 50 mK. The solid line is a fit of Eq. 1 to the data.

A. Delay line

The delay line device has an input transducer comprising two parallel IDTs with 20 finger pairs (one operating at a SAW wavelength of \( \lambda = 4 \) µm and the other at \( \lambda = 6 \) µm), a 2 mm separation, and a second transducer for output.

Fig. 1(a) shows the transmission of the delay line, \( S_{21} \), as a function of frequency at 50 mK. The attenuation of the cables in the cryostat has been subtracted. Both the \( \lambda = 6 \) µm and \( \lambda = 4 \) µm transducers are active. We observe multiple transmission peaks, with the fundamentals at \( f_1 = 446.4 \) MHz (arising from the \( \lambda = 6 \) µm transducers) and \( f_2 = 669.5 \) MHz (\( \lambda = 4 \) µm transducers), implying a SAW velocity of \( v \approx 2678 \) m/s under the IDTs. We find higher harmonics in the transmission spectrum at \( 3f_1, 3f_2, 5f_1, 5f_2, 7f_1 \) and \( 9f_1 \), demonstrating the possibility to operate ZnO SAW devices up to at least 4 GHz.

Simple interdigital transducers of the kind we use here are expected to give rise to a transmission spectrum close to the fundamental frequency that depends on frequency as

\[
|S_{21}| = A \cdot \text{sinc}^4 \left( N \Delta f / f_0 \right)
\]

where \( N \) is the number of IDT fingers, and \( \Delta f \) is the detuning from the center frequency \( f_0 \). Fig. 1(b) shows a measurement of the transmission spectrum close to \( f_1 \) and a fit to Eq. 1 demonstrating that the behaviour of our device is close to ideal.

Fig. 2(a) shows the transmission of the delay line measured at \( f_1 \) as a function of temperature. The temperature dependent attenuation of the cryostat cables has been calibrated out. The delay line transmission is only weakly temperature dependent below 50 K, but drops slowly at higher temperatures up to about 200 K, above which it drops very sharply. This decrease in transmission is accompanied by a shift in \( f_1 \); fitting the transmission to Eq. 1 to obtain \( f_1 \) at each temperature allows us to derive the change in the SAW velocity with temperature, as shown in Fig. 2(b).

At low temperatures, the ZnO substrate is not electrically conductive. However, at elevated temperatures thermal excitation of impurities leads to \( n \)-type doping and a non-zero conductivity. Fig. 2(c) shows the resistivity of our ZnO substrate as a function of temperature. Below about 120 K, the resistance is too high to measure using our apparatus. At higher temperatures, there are several intervals in temperature where the resistivity drops, which may be due to different impurities becoming ionised. These changes in resistivity are correlated with drops in \( |S_{21}| \), because the electric field component of the SAW can drive dissipative currents, thereby damping the SAW. The solid line is a fit of the function \( f(T) = A \cdot e^{-B/\rho(T)} \) to the data, where \( A = -38.3 \) dB and \( B = 2.65 \cdot 10^8 \) \( \Omega^{-1} \) are fit parameters. This model assumes that SAW dissipation is linear in the DC conductivity of the ZnO. Deviations from this simple model may be due to the frequency dependent absorption of different defect centres in the crystal.

Figure 2. (a) Transmission amplitude \( S_{21} \) of the fundamental mode \( f = 446 \) MHz of the delay line as a function of temperature \( T \). The solid line is a fit of transmission attenuating linearly with conductivity. (b) SAW velocity as a function of temperature, calculated by fitting the peak frequency and using \( v_{SAW} = \lambda_0 / f_{SAW} \). (c) Resistivity of the ZnO substrate as a function of temperature.
As the temperature increases from its base value, the quality factor decreases, and is particularly strongly temperature dependent as \( T \) approaches 1 K. This dependence is likely to be attributable to quasiparticle scattering in the Ti/Al bilayer, and its transition from the superconducting to normal state at \( T \approx 850 \) mK.

At base temperature, the quality factor \( Q_i \) reaches values near \( 1.5 \times 10^5 \), which is close to the highest quality factors reported in SAW resonators fabricated on other materials. It is interesting to note that in our device, superconducting electrodes increase \( Q_i \) by about a factor of 5.

### III. CONCLUSIONS

We have reported for the first time SAW devices on a bulk ZnO crystal substrate. Our results show that bulk ZnO devices are highly feasible at low temperatures, with resonator quality factors among the highest reported, while at high temperature, losses correlate with the bulk DC electrical conductivity. Such high quality SAW devices may find use in low temperature physics research such as quantum information science, where SAWs have already started playing a role.

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