1.2 Background and Motivation

1.2.1 Probing and controlling phenomena in quantum materials

Surface acoustic waves enable novel probes into quantum phenomena which are not accessible using conventional transport techniques. For example, SAWs were recently used to demonstrate that current-induced modifications of bubble and stripe phases in 2D electron systems (2DEs) are a local phenomenon [4]. In contrast to prior transport studies which indirectly probed the voltage drop on the edges of the 2DEs, the authors used SAWs to probe the entire sample at once, gaining new understanding into the effects of external current on highly-ordered electron phases. Another work used a combination of SAWs, microwave excitation, and optical detection to study quantum Hall stripes [5]. By employing SAWs with a wavelength of 60 nm, the authors were able to probe commensurability effects between the SAW superlattice and quantum Hall stripes. A plethora of earlier SAW-based studies provided new insight into the quantum Hall and fractional quantum Hall effect [6, 7, 8, 5, 9] and Wigner crystallization [10]. These works highlight the incredible strength of SAWs for probing phenomena in quantum systems. Building on these successes, researchers have begun to explore the potential of SAWs in the rapidly evolving field of 2D materials.

In 2018, interest in engineered 2D superlattices exploded with the discovery of unconventional superconductivity in twisted bilayer graphene [11]. The birth of the field of "twistronics" added a new knob to turn in the already massive parameter space available for creating bespoke 2D devices. By tuning the twist angle between two sheets of graphene (and thus the periodicity of the moiré superlattice), bilayer graphene can not only exhibit superconductivity, but also correlation-induced insulating states, magnetism, quantized anomalous

Hall states, and many more [12]. In 2D semiconductors, which exhibit exciton dynamics that are of great interest for next-generation electronics, tuning the moiré superlattice provides even more control over the spin and valley degrees of freedom [13]. While graphene has a lattice periodicity on the order of 0.15 nm, the moiré superlattices in twisted devices have much longer periods (tens to hundreds of nm) which are on the order of nominal SAW wavelengths. This congruence opens up the possibility of exploring commensurability effects between moiré superlattices and SAW potentials. Contactless probing using SAWs could also circumvent the challenges of making quality electrical contacts to 2D semiconductors for transport measurements [14]. Hence, SAWs are an ideal tool for contactlessly probing and controlling quantum phenomena in 2D materials. This potential has not gone unnoticed, as evidenced by recent works that have already employed SAWs to great effect, opening new avenues in the probing and manipulation of 2D quantum phenomena.

One phenomenon of interest is interlayer excitons in 2D semiconductor heterostructures. Interlayer excitons are composed of electrons and holes located in different layers in stacks of 2D semiconductors. Harnessing these excitons is exciting for nanophotonics and quantum information applications [15]; however, controlling them is difficult because they are charge-neutral and exhibit no net force under a uniform electric field. Prior works utilized diffusion to transport interlayer excitons, but the transport lengths achievable using diffusion are limited [16, 17]. In a recent work, the authors used SAWs to transport interlayer excitons over incredible distances in bilayer WSe_2 [18]. Given that SAWs transport both electrons and holes in the same direction (See Sec. ****), they can transport neutral excitons much further than the diffusion length. This approach also circumvents the challenges previously identified by other researchers when using local graphene gates [19]. In another work, SAWs were used as a contactless probe of measuring wave-vector dependent conductivity in ultra-clean graphene, establishing the viability of SAW resonant cavities as a probe for quantum transport phenomena in 2D materials [20]. However, these studies have only scratched the surface of what is possible by interfacing SAWs with quantum materials. Many other SAW-induced phenomena in 2D materials have been theoretically predicted, but not yet achieved experimentally [21]. Therefore, it is imperative to further develop the methods of interfacing SAWs with 2D materials, and to further our understanding of interactions between SAWs and quantum phenomena in 2D materials.

and

$$\Gamma = K^2 \frac{\pi}{\lambda} \left(\frac{(\sigma_{2D}/\sigma_M)}{1 + (\sigma_{2D}/\sigma_M)^2} \right). \tag{2.27}$$

Similarly to the bulk case (Eqs. 2.23 and 2.24), the SAW is dispersing and losing energy as it propagates through this conductive 2D material. However, the attenuation and dispersion is frequency-independent, and depends only on the ratio σ_{2D}/σ_M. This leads to an important question: Where does the lost SAW energy go?

2.2.4 The 2D acoustoelectric effect

Fal'ko and Iordanskii found that the oscillating electric field that co-propagates with the SAW imparts an effective force on charge carriers, driving a DC current that is proportional to the attenuation Γ [30]. In this section, I present the sketch of Fal'ko and Iordanskii's model given in Ref. [8], as I found their presentation easier to follow. Figure **??** shows a simplified illustration of a SAW propagating through a thin film. As previously discussed, a SAW is accompanied by a co-propagating electric field of the form

$$E(x,t) = E_0 \mathrm{e}^{i(kx - \omega t)}. \tag{2.28}$$

From Ohm's law, $E(x,t)$ creates a local oscillating current density

$$j(x,t) = \sigma E(x,t), \tag{2.29}$$

where σ is the conductivity of the thin film. This local current density causes electrons to coalesce in the wells of the SAW potential, as shown in Fig. **??**. Assuming that the amplitude of the perturbation in carrier density caused by the SAW (denoted by Δn) is much smaller than the average carrier density in the thin film (denoted by n_0), the periodic carrier density in the SAW takes the form [1]

$$n(x,t) = n_0 + \Delta n \mathrm{e}^{i(kx-\omega t)}. \tag{2.30}$$

Using the continuity equation $\partial J/\partial x = q\,\partial n/\partial t$, Δn can be written in terms of $E(x,t)$, giving

$$\Delta n(x,t) = -\frac{\sigma}{q}\frac{k}{\omega}E(x,t) = -\frac{\sigma}{q}\frac{1}{v}E(x,t) \tag{2.31}$$

Next, with $\Delta n \ll n_0$, and remembering that $\sigma = qn\mu$, σ can be expanded in terms of Δ_n, taking the form

$$\sigma(x,t) = \sigma_0 + \frac{\partial\sigma}{\partial n}\Delta n \mathrm{e}^{i(kx-\omega t)}. \tag{2.32}$$

Now, we can find the DC acoustoelectric current by plugging Eqs. 2.32 and 2.31 into 2.29 and taking the time average, giving

[1] If $\Delta n \geq n_0$, the perturbation in n can not be approximated as local, leading to the nonlinear acousto-electric effect. I discuss this further in Sec. 4.9.

$$
\begin{aligned}
j(x) = \langle j(x,t)\rangle &= \left\langle \left(\sigma_0 + \frac{\partial \sigma}{\partial n}\Delta n e^{i(kx-\omega t)}\right) E(x,t) \right\rangle \\
&= \left\langle \left(\sigma_0 - \frac{\partial \sigma}{\partial n}\frac{\sigma}{q}\frac{1}{v} E(x,t) e^{i(kx-\omega t)}\right) E(x,t) \right\rangle \\
&= \left\langle \sigma_0 E(x,t) - \mu \frac{\sigma}{v} e^{i(kx-\omega t)} E(x,t)^2 \right\rangle \\
&= -\frac{\mu}{v}\left\langle \sigma E(x,t)^2 \right\rangle .
\end{aligned}
\tag{2.33}
$$

One might initially consider the notion of an oscillating E-field creating a DC current to be counter-intuitive. However, we can now see that, though $\langle E(x,t)\rangle = 0$, a DC current arises from the cross-term $\langle \sigma E(x,t)^2\rangle$, which corresponds to the time-averaged Ohmic power dissipated by the charge carriers in the thin film. So far, this model considers a local perturbation in n from the SAW; therefore, this cross-term can be thought of as the local dissipation of SAW power by charge carriers in response to the co-propagating electric field.

Finally, we need to relate Eq. 2.33 to Γ. Remembering that Γ describes the loss in SAW intensity per unit length, the SAW intensity can be written in the form

$$
I(x) = I_0 e^{(-\Gamma x)}. \tag{2.34}
$$

Rearranging and differentiating I with respect to x, Γ takes the form

$$
\Gamma = \frac{1}{I}\frac{\partial I}{\partial x} = \frac{1}{I}\left\langle \sigma E(x,t)^2 \right\rangle . \tag{2.35}
$$

Then, combining Eqs. 2.33 and 2.35, the DC acoustoelectric current density becomes

$$j = -\frac{\mu}{v}\left\langle \sigma E(x,t)^2 \right\rangle = -\frac{\mu}{v} I\Gamma = -\frac{\mu I}{v}\frac{K^2}{2\lambda}\left(\frac{(\sigma_{2D}/\sigma_M)}{1+(\sigma_{2D}/\sigma_M)}\right). \tag{2.36}$$

Equations 2.26, 2.27, and 2.36 are central to interactions between SAWs and quantum materials. In Sec. 4.6, we modify this classical relaxation model, which assumes charge carriers of a single type, to describe mixed-carrier transport in graphene.

2.3 Surface acoustic wave generation

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