I. INTRODUCTION

Over the last few decades, thermoelectric effects have emerged as powerful tools to study the electronic properties of materials. Being intimately connected to the electrical conductivity $\sigma$ and thermal conductivity $\kappa$, the thermoelectric conductivity $\alpha$ provides different, but complimentary information. In the case of metals and semiconductors, the diagonal component $\alpha_{xx}$ of the thermoelectric tensor $\alpha$ is the dominant thermoelectric response \[1,2\]. The off diagonal elements, which typically appear only in the presence of a magnetic field, are usually small due to generic symmetries of the Fermi surface. In the case of superconductors, the dominant response is off-diagonal component $\alpha_{xy}$, and the diagonal response is vanishingly small. This is because in superconductors, the source of the thermoelectric effects is primarily superconducting fluctuations rather than quasiparticles as in the case of metals. Since superconducting fluctuations are carriers of entropy, like electrons they travel down the temperature gradient, generating a transverse phase-slip voltage in the process. Being a signal arising purely from superconducting fluctuations, measurement of $\alpha_{xy}$ becomes particularly interesting in the field of 2D disordered superconductors.

The physical property that is accessible in a thermoelectric measurement is the Nernst effect, i.e. the transverse voltage per unit temperature gradient in the presence of perpendicular magnetic field: $N = \frac{\partial V}{\partial T}|_{B(z)\rightarrow 0}$ and the Nernst coefficient $v = \frac{\partial N}{\partial B}|_{B(z)\rightarrow 0}$. In the case of superconductors which are characterized by an effective particle-hole symmetry, the Nernst coefficient can be expressed as a product of the resistivity and the transverse Peltier coefficient $v = \rho_{xx} \cdot \alpha_{xy}$. During the past few years the Nernst effect has been shown to be a very effective tool to study vortex motion in the fluctuation regime both above and below $T_c$ \[3,8\].

In 2D superconductors Nernst effect measurements become especially appealing due to several exotic vortex phases which are expected in these thin films. These system often undergo a direct superconductor to insulator transition as a function of thickness or disorder. Experiments have revealed signs for cooper pairing and an energy gap in the insulating phase and theories have predicted the presence of preformed pairs or emergent electronic granularity leading to superconducting islands embedded in an insulating matrix even on the insulating side of the transition. Such a phase has been dubbed a “Bosonic insulator” and is associated with the presence of a pseudogap above the transition temperature or in the insulator. This is understood in the framework of the “Charge-Vortex Duality” model: In the superconducting phase Cooper pairs are condensed into a superfluid leading to $\rho = 0$. Here Vortices are Bosonic excitations introducing dissipation and causing finite $\rho$. In the insulating phase Vortices are condensed in a collective mode with zero conductivity ($\sigma = 0$) and Cooper pairs are Bosonic excitation contributing to a finite $\sigma$. An example is a thin film of amorphous indium oxide a-InO$_x$ in which evidence for vortices motion has been detected in the insulator \[9,13\]. Indeed, significant Nernst coefficients have been measured in both the superconducting and the insulating phases \[8\].

Experiments on other systems \[14,17\] and theories \[18,19\] have also raised the possibility of an intermediate anomalous “Boson metal” phase between the insulator and the superconductor. Such a phase, that contradicts the accepted notion that a 2D metallic state cannot exist, is under heavy deliberations nowadays \[20\] and Nernst measurements may assist in the elucidation of this issue.

In yet other systems like MoGe, an exotic hexatic vortex fluid is encountered on the approach to the zero-resistance state in the presence of a magnetic field \[21\]. By studying the field dependence of the Nernst signal in systems like these, the characteristic length scales associated with superconductivity can be extracted, giving information about the underlying physical processes both at the microscopic and mesoscopic level.

In high-$T_c$ cuprates, the Nernst effect has been used extensively to attempt to understand the nature of the pseudogap state \[3,4\]. The nature of the pseudogap state of High-$T_c$ cuprates like YBCO is being hotly debated even to this day, with suggested explanations diverging between two key ideas, a fluctuation-dominated pseudogap phase with preformed Cooper pairs, and a competing-order hypothesis that describes the pseudogap state as a competing ground state.
with a magnetic order. Nernst effect, originating purely out of superconducting fluctuations has played a key role in being complimentary to electrical conductivity measurements, and has helped to refine the phase diagrams of many such systems [3,22,23].

In semimetals like bismuth and graphite, Nernst effect is of electronic origin, and shows Landau quantization in the form of oscillatory response to a magnetic field in the lines of de Haas-van Alpen and Shubnikov-de Haas oscillations [24,28]. Based on these observations, Nernst effect has emerged as a new tool to study the Fermi surface properties of 2d materials like graphite [29]. Anomalous Nernst effect, like anomalous Hall effect may arise even at zero magnetic field in materials such as Weyl semimetals, which have non-zero Berry curvature of the reciprocal space [30–34]. A special form of the anomalous Nernst effect is observed in materials with strong spin-orbit interaction. Termed as the spin-Nernst effect [35,36], it is an accumulation of electronic spins, instead of charge in a direction transverse to the heat flow, caused by the differential scattering of up-spin and down-spin electrons by the heavy element atoms.

Thus clearly, the Nernst effect has a rich phenomenology and is an important tool to study the physics of several classes of materials. It should be noted that the Nernst response is typically varies over many orders of magnitude with temperature but seldom exceeds a few µV/K. Information is often contained in regimes where the signal is only a few nV, which makes precise measurement of utmost importance. Several factors need to be considered to make accurate measurements of the Nernst effect. (i) The sample and measurement leads should be shielded from ambient electromagnetic radiation (ii) Thermoelectric voltages at junctions of measurement wires must be carefully compensated (iii) A large-enough temperature gradient should be generated for producing measurable signal (iv) The temperatures and temperature gradients must be accurately determined. This is achieved by making heat transfer between the substrate and the heater/sample/thermometers to be efficient. In the present article we describe a method suitable for the measurement of magneto-thermoelectric effects of thin film samples at low temperatures in the range ~ 0.3K to 10K.

II. EXPERIMENT

A. Samples

The thermoelectric setup, comprising a heater, two thermometers and the sample are fabricated on a chip of MEMpax™ borosilicate glass substrates of dimension 1cm × 1cm × 0.3mm by optical lithography, see Fig. 1. A gold meander serves as a heater. It is fabricated out of 30nm thick Au with a 4nm underlayer of Cr, and is designed to have a resistance of 200Ω at room temperature. The two thermometers are fabricated from e-beam evaporated Indium Oxide, with the growth parameters being tuned to achieve moderately insulating behaviour (4Ω ~ 10 – 200kΩ at low temperature). The sample is usually grown by standard thin film deposition techniques like thermal/ebeam evaporation, pulsed laser ablation etc. Layered 2d materials can also be used as samples using the van der Waals transfer method with suitable modifications to the electrical leads. The choice of substrate is dictated by the requirement of having a very low thermal conductivity which enables the setting up of a large enough heat current without the application of excessive heating power. Glass has a thermal conductivity in the range of 0.01W/m·K at 1K, among the lowest of all materials. Glass is also a natural choice when the films to be grown are of amorphous nature. The glass substrate is suspended from the cold finger in the manner shown in Fig.1e, thermal contact being provided on the substrate edge far from the heater.

B. DC measurement

In the absence of standard R-T characteristics, the thermometers are calibrated through a measurement of R-T curves against calibrated sensors in the cryostat prior to the measurement. Temperature gradients are then measured as a function of the applied heater current, which forms the second part of the calibration in the case of DC measurements. \( ΔT_{DC} = T_{DC}^2 - T_{DC}^1 \). \( V T_{DC} = ΔT_{DC} / (X_2 - X_1) \). In Fig.2 the temperature difference between the two thermometers is plotted as a function of current through the heater for different devices along with a simulated curve generated from a finite element method using known material parameters. The were found to be in reasonable agreement. Calculated isotherms indicated no transverse temperature gradients at the sample position (Fig.2e) and no significant non-linearity in the tem-

![Image](https://via.placeholder.com/150)
FIG. 2. (color online) Temperature difference between two thermometers as a function of heater current (DC) : Comparison between experimental points (symbols) and finite element modelling (blue line). Inset (a) Isothermal contours with a 1 mA heater current obtained by finite element modelling. Inset (b) Temperature profile in a direction parallel to the heat current.

FIG. 3. (color online) DC Nernst responses of a 30nm thick weakly superconducting amorphous Indium oxide

C. AC measurement

This technique involves driving the heater with a sinusoidal AC current. An AC heating current at frequency \( \omega \) generates a heating power which has 2 components: a constant background and an oscillating component with a frequency 2\( \omega \). The temperature gradients set up as a result can be similarly divided into two components. The measurement involves detection of the transverse voltage at a frequency of 2\( \omega \) by lock-in techniques. Calibration of the set-up involves the additional step of measuring the AC component of the temperature gradient \( \nabla T_{AC} \). When the temperatures of the two thermometers are in phase, \( \nabla T_{AC} \) can be simply estimated from the difference in the temperature amplitudes at the two thermometers \( \Delta T_{AC} = T_{1AC} - T_{2AC} \), \( \nabla T_{AC} = \Delta T_{AC}/(X_2 - X_1) \). However, factors like thermal conductivity and specific heat of the substrate generally cause the phase difference to be non-zero even at low frequencies. So an additional goal of the calibration is to find an optimal frequency that is high enough for a lock-in measurement to be practical, at the same time low enough for phase difference between thermometers to be small. \( \omega \) also needs to be low enough for the amplitudes \( T_{1AC} \) and \( T_{2AC} \) to be large. This has to be found experimentally, because even the simplest analytical treatment of such a situation gives rise to complicated expressions for the gradient and phase, whose applicability to real-world systems is unclear. The result of one such optimization is shown in Fig. 5. At very low frequencies like 0.5 Hz, the phase difference is small, and increases monotonically with increasing frequency. It is also found to increase with increasing temperature, which probably reflects the different temperature dependences of the two factors, specific heat and thermal conductivity, which determine the relaxation time, \( \tau = C_p/K \). We choose 1Hz for our measurements, which provides the right compromise be-
between ease of measurement and small phase difference. In Fig. 5b, the instantaneous temperatures are plotted together with the heater current and power at 1Hz driving frequency and a setpoint of 4K. Interestingly, even though the phase difference between the two thermometers is minimal, a substantial frequency dependent phase shift exists between the heater power and the two thermometers. This is another effect of the finite thermal relaxation time of the substrate, and causes the Nernst signal to appear almost entirely in the Y-channel of the lock-in amplifier for these settings.

Measurement of the Nernst signal is carried out using an EG&G 7265 lock-in amplifier and SR552 and SR560 preamplifiers. The former, with an input impedance of 100kΩ and an input noise level of ∼1nV/√Hz at 2Hz was used as the first stage and is connected directly to the sample leads. Its output is fed to the SR 560 where it is sent through a built-in band-pass filter with a passband of 0.3Hz to 10Hz and amplified by a factor of about 1000 before being sampled by the lock-in amplifier. The lock-in operation is carried out with a time constant of 10sec, giving it a bandwidth of 0.1Hz and the resultant noise level is in the range of 1nV. Fig. 4c shows the results of the AC Nernst measurement for the low field regime of the MoGe sample. A clear reproducible signal is visible in a region that was completely overshadowed by noise in the DC measurement. With minimal signal processing, a noise level in the range of 300pV was obtained, a vast improvement over the >30nV noise level in the dc measurement for this sample (Fig. 4b).

D. Artefacts

A drawback of a one-heater-two-thermometer thermoelectric setup is that it is difficult to control the temperature and temperature gradient independently. For DC measurements, the temperature of the sample is obtained by interpolation between the two thermometers. The same is applicable to an AC measurement when the phase difference between the thermometers is low enough. But there is no easy way of obtain-
FIG. 6. (color online) Corrupted Nernst signal as a function of magnetic field due to artefacts mentioned in the text. Sample is MoGe of thickness 25 nm. Heater current is 5mA with a cryostat temperature of 4K.

The $T_{DC}$ and $\nabla T_{AC}$ when higher frequencies are used apart from direct measurement of the demodulated signal with an oscilloscope as shown in Fig. 5b. This can make measurements slow at higher frequencies above 2Hz.

A second artefact arises when a current of a large amplitude $\gtrsim 3$mA is used for driving the heater. While this creates a larger $\nabla T_{AC}$ which improves the S/N ratio, a contribution from $T_{AC}$ starts to influence the observed readings. Put simply, the AC voltage measured in a lock-in measurement is composed of two parts:

$$\frac{dV}{dT}(T, \nabla T) = \frac{\partial V}{\partial T} \bigg|_{T} \frac{d\nabla T}{dt} + \frac{\partial V}{\partial \nabla T} \bigg|_{\nabla T} \frac{dT}{dt}.$$  

The first part constitutes the Nernst response of the sample, while the second is an artefact with no physical significance. It which is small under normal circumstances, But when measuring the Nernst response of a superconductor, the second term can become very important close to the sample’s $T_{c}$ when the resistance of the sample changes rapidly with temperature. There is no easy way of separating these two components, and at high temperatures and magnetic fields, the spurious voltage can dominate the measured transverse voltage. This is illustrated in Fig. 6 for an AC heater current of 5mA at a setpoint of 4K, the sample being superconducting MoGe with a $T_{c}$ of 7K.

III. CONCLUSIONS

We have developed a thermoelectric measurement setup suitable for thin films and 2D van der Waals stacked samples at low temperatures. With the heater and thermometers fabricated on-chip, the setup minimizes thermal lags, thus enabling accurate measurements of temperatures and reliable AC measurements. We have developed comprehensive protocols for measurements in DC and AC modes. In DC mode, the noise levels can be reduced down to 7-9 nV with appropriate signal conditioning. In AC mode with severely restricted bandwidth, a noise level of 0.3-1 nV is obtainable. This one-heater-two-thermometer setup is particularly suited for the measurement of 2D superconducting thin films, for which Nernst effect measurement is an important tool to study quantum fluctuations. The low noise level makes it feasible to employ techniques of noise measurement to study fluctuations in thermoelectric effects, which has been predicted to be a useful tool in several branches of condensed matter physics, including the search for Majorana states in condensed matter systems [40, 41], study of vortex phase transitions in superconductors [42] and the study of spin-Seebeck effects [43].

ACKNOWLEDGMENTS

The authors would like to thank Pratap Raychaudhuri and John Jesudasan of Tata Institute of Fundamantal Research, Mumbai, India, for providing the MoGe samples and Kamran Behnia of CNRS, France for valuable discussions. This research was supported by the Israel science foundation, grant No. 783/17.

The data presented in this manuscript are available from the corresponding author upon reasonable request.

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