Visualizing dissipative transport dynamics at the nano-scale with superconducting charge qubit microscopy

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(Dated: October 10, 2019)

The investigation of novel electronic phases in low-dimensional quantum materials demands for the concurrent development of measurement techniques that combine surface sensitivity with high spatial resolution and high measurement accuracy. We propose a new quantum sensing imaging modality based on superconducting charge qubits to study dissipative charge carrier dynamics with nanometer spatial and high temporal resolution. Using analytical and numerical calculations we show that superconducting charge qubit microscopy (SCQM) has the potential to resolve temperature and resistivity changes in a sample as small as $\Delta T \lesssim 0.1$ mK and $\Delta \rho \lesssim 1 \cdot 10^4 \Omega \cdot \text{cm}$, respectively. Among other applications, SCQM will be especially suited to study the microscopic mechanisms underlying resistive phase transition, such as the superconductor-insulator-transition in twisted bilayer graphene, to investigate novel topological boundary modes found in higher order topological insulators and to optimize the transport properties of nano- and mesoscopic devices.

Introduction. Over the past decades, a plethora of novel quantum materials has been discovered, in which the notion of topology and electronic correlations fundamentally affect their electronic properties. Dissipation-less helical edge transport in higher order topological insulators [1][2] and correlated insulating and superconducting states in magic angel twisted bilayer graphene [3][4] represent only two recent examples, which promise new insights into questions of topological matter and many-body physics and which carry the prospect of potential technological applications such as spintronic devices and topological quantum computation.

To date, most insights on these phenomena are derived from transport experiment that measure a global resistance drop across a device made from these materials, for instance as a function of temperature or magnetic field, with the goal to elucidate the underlying physical mechanisms. Such non-local measurements are however inherently insensitive to charge carrier dynamics at small length scales and cannot resolve local scattering mechanisms as well as charge carrier interaction effects resulting in the measurable resistance drop across the device. Experimentally investigating the electrical transport properties of these quantum materials therefore demands for the concurrent development of new experimental techniques that combine surface sensitivity with high spatial resolution and high measurement accuracy.

Quantum sensing microscopy probes, which harness the sensitivity of a two-level quantum system to perturbing fields from the environment, have started to fill out this gap recently [5]. Scanning NV center microscopy has proven especially versatile to study spin ordering [6], 2D magnetism [7], as well as to measure the temperature and conductivity on the surface of metallic samples down to temperatures of a few Kelvin with few tens of nm spatial resolution [8][9]. Scanning SQUID on tip thermometry [10], as a related technique, has evolved as a valuable tool to study nano-scale energy dissipation in devices made from 2D materials addressing questions such as angle variations in twisted bilayer graphene with spatial resolution better than 200 nm [11]. Recent advances in technology have also promoted microwave impedance microscopy as a powerful tool to study the resistivity of a sample [12], and helped to visualize the topological edge states on the perimeter of an insulating bulk [13].

Scanning Charge Qubit Microscopy. We here propose Scanning Charge Qubit Microscopy (SCQM) as a new quantum sensing imaging modality based on superconducting charge qubits (CQ) to study dissipative charge carrier dynamics with estimated nanometer spatial and high temporal resolution. Superconducting CQs, such as the Cooper pair box [14], are inherently sensitive to charge noise $\delta n(t)$ in the immediate environment, which induces quantum decoherence and limits the qubit’s coherence time to about a microsecond [15][16]. This high sensitivity to charge noise renders this type of qubit less suitable for quantum computation applications, but on the other hand, makes it a prime candidate for quantum sensing applications, in which charge noise $\delta n(t)$ acting on the CQ can serve as a valuable spectroscopic tool.

This noise spectroscopy concept we here describe is based on the physical phenomenon that the equilibrium stochastic motion of charge carriers in conducting materials of resistance $R$ gives rise to Johnson-Nyquist noise. At finite temperature $T$ and in the limit of low-frequencies at $k_B T \gg \hbar \omega$, this type of noise can be characterized by its voltage noise spectral density $S_V = 4k_B T R (k_B - \text{Boltzmann’s constant}, \hbar - \text{Planck’s constant}, \omega - \text{frequency})$ [17][18]. Measuring Johnson noise in and out of equilibrium, e.g. in the presence of an external drive current $I$, allows to characterize a sample’s resistance and quantify the underlying charge carrier dynamics by tracking temperature changes through scattering-induced energy dissipation. In addition, such measurements can also help to distinguish between different transport regimes, such as diffusive and ballistic transport [19].

Dissipative transport characteristics in a sample can be probed using a CQ with the help of a coupling capacitor $C_C$. The capacitance serves as a mediator effectively converting voltage fluctuations $\delta V$ in the sample into charge noise on the qubit. For sufficiently large $C_C$ values, voltage fluctuations in samples can therefore induce decoherence on a prepared quantum state of the CQ.
Decoherence of the CQ (and generally any two-level quantum system) resulting from that interaction can be quantified by measuring its decoherence time $T_2$, for instance by using microwaves in a circuit quantum-electrodynamics (cQED) setup. Importantly, a cQED realization with GHz bandwidth allows for time-resolved studies using a pulsed measurement scheme, which could facilitate the investigation of dissipative transport characteristics. The Josephson energy $E_J$ can be adjusted through the gate voltage $V_G$. The CQ therefore constitutes a two level quantum system.

Decoherence in a charge qubit. In the most simple implementation, the CQ corresponds to a charge island formed between a Josephson junction, characterized by the coupling energy $E_J$ and its capacitance $C_J$, and a gate capacitance $C_G$, which allows to adjust the island charge $n_G = C_G V_G / 2e$ in units of Cooper pairs through applying a gate voltage $V_G$ (elementary charge) (Fig. 1(b)). In the limit of the charging energy $E_C = e^2 / 2C_G$ exceeding the Josephson coupling energy $E_C \gg E_J$, the system can be reduced to the two lowest charge states of the island $|↑⟩$ and $|↓⟩$, respectively. $E_C$ is determined by the total capacitance to ground as $C_S = C_J + C_G$ and possible other contributions, such as the coupling capacitance $C_C$. In this case, the effective Hamiltonian can be rewritten in a form of a fictitious spin-1/2 particle, $H = -E_{el} / 2\sigma_z - E_J / 2\sigma_x$, under the influence of the pseudo-magnetic fields $B_x = E_{el}$ and $B_y = E_J$ with the electrostatic energy $E_{el} = 4E_C(1 - 2n_G)$.

The charge dispersion of $H$ is shown in Fig. 1(c) and illustrates the role of $E_J$ as a symmetry breaking term that lifts the degeneracy of $|↑⟩$ and $|↓⟩$ states at a gate charge of $n_G = 0.5$. This yields results in a gapped excitation spectrum with the level splitting $\Omega_0 = \sqrt{E_{el}^2 + E_J^2}$. For a given gate charge, the CQ therefore constitutes a two level quantum system, the coherent superpositions of which can be mapped onto a Bloch sphere (cf. Fig. 1(a)).

Interaction with a dissipative environment can lead to decoherence and relaxation of a prepared CQ state, the strength of which is determined by the CQ properties and the coupling strength between the CQ and the environment. Voltage noise $\dot{\delta V}(t)$ present in the environment will be converted to gate fluctuations.
charge noise $\delta n_G(t)$ through the coupling capacitance $C_C$. In the limit of $E_C \gg E_J$ this process will, in first order, only result in longitudinal charge fluctuations of the gate charge $(\delta n_G(t))|\sigma_g$, which can be rationalized in terms of a coupling Hamiltonian $H_C(t) = 4E_C\sigma_g \delta n_G(t)$ \cite{28}. Owing to this noise term, a prepared quantum superposition of a CQ state will experience dephasing described by $\Delta \phi = \int_{-\infty}^{\infty} dt H_C(t)$ \cite{29}.

![Image 55x386 to 298x630](image_url)

**FIG. 2: Microwave read-out of CQ decoherence.** (a) Realistic design drawing to scale of a resonator charge qubit implementation for SCQM. The red patches are the launchers for coupling to the circuitry, the coplanar strip-line (CPS) is shown in blue is characterized by its photon decay rate $\kappa$ and resonance frequency $\omega_r$ (scale bar). Inset: The CPS couples to the qubit, characterized by its Josephson energy $E_J$ and charging energy $E_C$, through coupling capacitances (red pads) with strength $g$. The tip for realizing local probe capabilities is galvanically coupled to one of the capacitance pads (scale bar). (b) Calculated homodyne phase shift of the cavity tone as a function of the applied spectroscopy frequency tone $\omega_s$ for different indicated linewidth $\nu_s$. (c) Calculated change of the phase shift peak maximum $\phi_{\text{peak}}$ in (b) with respect to changes in the sample’s temperature $T$ times normalized resistance $\epsilon$.

On this basis, it is possible to quantify the dephasing of a CQ state as resulting from Johnson noise in the capacitively coupled environment. The magnitude of the resulting charge noise spectral density on the qubit $S_n = gS_v$ is determined by the transfer function $g = (\eta C_C/2e)^2$, which we assume to be frequency-independent for now. The scaling factor $\eta = C_C/C_S$ renormalizes $C_C$ to an effective value. Analyzing the dephasing $\Delta \phi$ in terms of the phase-phase correlation function in the low frequency limit \cite{29}, one can write the charge noise induced dephasing time as $1/T_{2M} = 8\pi^2 (k_B T/h)\eta^2$, with $\epsilon = R/R_Q$ as the normalized resistance and $R_Q$ as K\litzing’s constant \cite{29}. Measuring the CQ dephasing characteristics therefore allows to directly determine the resistance and temperature of a sample, which is capacitively coupled to the CQ. Remarkably, the change of the dephasing constant $2\pi\nu_s = 1/T_{2M}$ with respect to changes of a sample’s resistivity and temperature $\partial \nu_s/\partial (\epsilon T) = 4\pi(k_B T/h)\eta^2$ is constant, rendering the CQ an ideal quantum sensor with linear output characteristics.

**Microwave read-out of CQ dephasing.** The qubit state and its dephasing characteristics can be interrogated using microwave photons in a cQED architecture. In the example shown in Fig. 2(a), the qubit is capacitively coupled to a superconducting coplanar strip-line resonator (CPS) of bare frequency $\omega_r$ in a reflective read-out scheme. In the limit of strong coupling $g > \kappa, \gamma$, in which the resonator-qubit coupling $g$ exceeds the inverse cavity and qubit lifetime $\kappa$ and $\gamma$, respectively the CQ states $(|\uparrow\rangle$ and $|\downarrow\rangle$) are entangled with the resonator photon number states $|n\rangle$. At large detuning $\Delta = \omega_r - \Omega_0$ between CQ and resonator, this entanglement results in a dressed resonator frequency $\omega_d = \omega_r \pm g^2/\Delta$, which depends on the qubit state $(+\uparrow\rangle$ and $-\downarrow\rangle$). In this so-called dispersive limit, the qubit state can be therefore be measured by measuring the phase shift $\phi = \pm \tan^{-1}(2g^2)/(\kappa \Delta)$ of the reflected microwave photons when driving the cavity at its bare frequency $\omega_r$ \cite{26}.

An additional spectroscopy tone $\omega_s$ allows to excite transitions between the qubit states and create arbitrary quantum superpositions of $|\uparrow\rangle$ and $|\downarrow\rangle$. Importantly, such two-tone spectroscopy yields a strong (no) phase shift for the reflected microwave signal in a homodyne detection scheme, when $\omega_s$ is on (off) resonance with the qubit transition. This is illustrated in Fig. 2(b), which shows a calculated spectroscopy tone sweep across the $|\uparrow\rangle-|\downarrow\rangle$ transition.

Based on these read-out modalities, the dephasing characteristics of the CQ can be determined. Most commonly, pulse sequence experiments such as Ramsey fringe or spin-echo are used to measure the $T_2$ time with high accuracy \cite{29}. However, determining the qubit dephasing through observing the quantum state evolution at different pulse delays in these experiments typically results in long measurement times on the order of minutes to hours. In the context of SCQM, this approach appears less suited from a practical perspective, as mapping out $T_2$ on a $256 \times 256$ point grid would result in measurement times on the order of a day or more.

We propose an alternative approach for determining the dephasing characteristics that lends itself to fast measurement schemes and is key to this SCQM proposal. It is based on a line shape analysis of the spectroscopy tone sweep shown in Fig. 2(b), which facilitates to determine the $T_2$ time of the CQ. In the low power limit of $n_S \rightarrow 0$, in which only few photons $n_S$ are occupying the resonator at $\omega_s$, the line shape of the phase peak can be approximated by a Lorentzian function $f(\omega_s, \nu_s)$, the half-width half-maximum $\nu_s$ of which is directly related to $T_2$ through $2\pi \nu_s = 1/T_2$ \cite{19}. Crucially, owing to its Lorentzian nature, the maximum (minimum) of the phase peak (dip) is directly proportional to the dephasing time $f_{\text{max}} = 1/(\pi \nu_s) = 1/(2\pi^2)T_2$. Hence, in the limit
We want to point out that the reciprocal dependence of \( f_{\text{max}} \propto (\epsilon T)^{-1} \) on the resistance and temperature, renders this detection scheme highly responsive to even smallest changes in these quantities, as illustrated in Fig. 2(c). Finally, this detection scheme utilizing two tone spectroscopy at fixed frequencies realizes a fast read out of the qubit decoherence characteristics and should facilitate imaging of the local dissipative transport properties on a sample surface in a realistic experimental time frame.

**Fundamental design considerations.** The ability of SCQM to measure dissipative transport dynamics in a capacitively coupled sample depends on the intrinsic CQ properties, on the SCQM device architecture and on the coupling geometry. Crucially, the detection of dissipative transport induced qubit decoherence requires that its rate \( \nu_{\text{M}} \) exceeds the intrinsic qubit dephasing rate \( \nu_\phi \) in order to yield a measurable signal in the total dephasing signal \( 1/T_2 = 2\pi\nu_\phi = 2\pi(\nu_\phi + \nu_M) = 1/(T_{2\text{M}} + 1/T_\phi) \approx 1/T_{2\text{M}} \) for \( \nu_M \gg \nu_\phi \).

The typical experimentally found intrinsic dephasing time of superconducting CQ owing to 1/f-charge noise is about \( \nu_\phi \approx 320 \text{kHz} \) \( \cite{16} \), which sets the lower bound for the minimum required external dephasing rate \( \nu_{\text{M}} \) and thus, defines realistic boundary conditions for the experimental design.

To meet this requirement, the response of the CQ to changes in the sample’s temperature and resistivity, \( \partial \nu_{\text{M}}/\partial (\epsilon T) \propto \eta^2 \), can be significantly enhanced by maximizing the coupling capacitance \( C_\Sigma \) and, at the same time, by minimizing the total capacitance to ground \( C_S \), such that \( \eta \rightarrow 1 \). Fig. 3(a) illustrates that enhancing the renormalized coupling capacitance \( \eta \) by one order of magnitude already increases the response of the CQ by two orders of magnitude. We have performed electrostatic simulations of the resonator-CQ-tip-sample geometry (Fig. 2(a)) with the goal of minimizing \( C_S \) as well as to obtain a realistic estimate for \( \eta \) \( \cite{29} \). Our simulations show that using an optimized CPS design allows to reduce the total capacitance \( C_S \) to values as small as a few femtofarad and, at the same time, maintain large coupling values \( g > 100 \text{MHz} \) as is required for the previously described dispersive readout scheme. We note that those values obtained from our simulation are comparable to previously reported values, which were obtained from experiments on Cooper pair boxes \( \cite{16} \). Key CPS design aspect is to minimize the surface area of the capacitor pads that couple the Josephson junction to the resonator (Fig. 2(a) inset).

Concerning the realization of sufficiently large \( C_\Sigma \) values, one has to find the right balance between, on the one hand maximizing the geometric capacitance for obtaining a high response and, on the other hand maintaining a high spatial resolution. Using a thin conical wire of both length and base diameter of \( 5 \mu\text{m} \) as a tip attached to one of the capacitor pads (see Fig. 2(a) inset), our analytical calculations show that renormalized coupling capacitance values of \( \eta \approx 0.1 \) and an effective spatial resolution of \( \Delta x \leq 200 \text{nm} \) can be achieved \( \cite{29} \). In this case, the spatial resolution is limited by the geometrically distributed stray capacitance of the tip wire. Using a thin superconducting nano-wire with a diameter of \( 50 \text{nm} \) as an alternative still allows to reach values of \( \eta > 0.01 \) but with a much enhanced spatial resolution of \( \Delta x \leq 50 \text{nm} \). Ultimately, one can choose an appropriate coupling tip based on the requirements of an experiment for the spatial resolution and the sensor response.

**Response and sensitivity of SCQM.** Based on these considerations it is possible to calculate the response of the CQ to changes in temperature, \( \Delta T \) and resistance, \( \Delta R \), respectively of a capacitively coupled sample, that is the change of the detected phase maximum with respect to these quantities (cf. Fig. 2(b)) \( \cite{29} \). The calculated response \( \phi(\Delta T) \) of the CQ to a temperature change is displayed Fig. 3(b) and illustrates the high sensitivity of the CQ to even smallest changes in temperature in this experimental concept. Using realistic setup parameters (see caption), our calculations reveal that a temperature change of \( \Delta T = 1 \text{mK} \) already induces a 10% change in the measured homodyne phase shift. The calculated response to a resistance change \( \phi(\Delta R) \) in Fig. 4(b) displays similar sensitive characteristics a change of \( \Delta R = 10 \Omega \) reduces the phase maximum by \( \approx 50\% \).

Ultimately, the signal-to-noise ratio (SNR) and the attainable sensitivity of SCQM to temperature and resistance changes are determined by the noise level of the amplification line for the microwave signal. Its noise is commonly dominated by the number of thermal photons \( n_D = k_B T_D/(\hbar \omega) \), generated in the high-electron-mobility-amplifier (HEMT) used to amplify the microwave signal at cryogenic temperatures \( (T_D = 4 \text{K}) \). A conservative estimate of that number for our concept yields \( n_D \approx 100 \). In a homodyne detection scheme at \( g^2/(\kappa \Delta) \gg 1 \), we can then define the SNR = \( \sqrt{m(n_D/n_D)} \), where \( m \) corresponds to the number of measurements and \( n_D = n_D T/2 \) to the number of collected photons during a finite integration time \( \tau \). If we assume a cavity enhanced CQ lifetime of \( 1/\gamma = (\Delta/g)^2 \kappa^{-1} \approx 100 \mu s \) and operate our read-out in the low power limit \( n \leq 10 \), we can define a theoretical upper bound to the attainable SNR = \( 5 \sqrt{m} \), for \( \tau = 1/\gamma \). Considering an experimentally determined CQ lifetime of \( 1/\gamma \approx 2 \mu s \) for superconducting charge qubits \( \cite{16} \), we obtain a realistic SNR estimate of \( \text{SNR} = 10^{-1} \sqrt{m} \). Hence, with large amount of averaging \( (m > 10^6) \) a SNR > 100 can be realized, which should facilitate a temperature and resistivity resolution of \( \Delta T \leq 0.1 \text{mK} \) and \( \Delta R \leq 0.1 \Omega \). Assuming a tip diameter of \( 50 \text{nm} \), a change in resistivity of \( \Delta \rho \leq 1 \times 10^8 \Omega \cdot \text{cm} \) could be resolved.

Fast scanning operation of SCQM, on the other hand (256 x 256 grid, total measurement time \( t < 30 \text{min} \)), can be realized with moderate averaging \( (m = 10^4) \). This results in \( \text{SNR} = 10 \), which still allows to detect temperature and resistivity changes as small as \( \Delta T \approx 1 \text{mK} \) and \( \Delta \rho \leq 5 \times 10^3 \Omega \cdot \text{cm} \). If a higher sensitivity of the CQ sensor is required, using Josephson parametric amplifiers instead of HEMTs could enhance the SNR and, consequently the resolution by up to two orders
of magnitude \[30\].

**Discussion.** To discuss the perspectives of SCQM in the context of quantum materials, it is instructive to review the current state of related measurement techniques. Table I contrasts the capabilities of existing microscopy techniques to probe dissipative transport with the estimated performance of SCQM. Among those techniques, scanning NV microscopy represents the perhaps most versatile tool with demonstrated capabilities of tracking the electrical conductance and temperature of a sample with nanometer spatial and, in principal, picosecond temporal resolution across a large temperature range down to 4 K \[9\]. Thermal imaging using a SQUID on tip (tSOT) operating at temperatures down to 300 mK, offers DC thermal imaging capabilities with an unprecedented temperature resolution of \(\Delta T \leq 1 \mu K\) and a spatial resolution of about 100 nm \[10\]. Scanning microwave impedance microscopy is a tool specialized on imaging the resistivity of a sample with about 100 nm spatial resolution on a variable temperature range down to 2 K \[12\]. SCQM on the other hand, offers resistivity and temperature sensing modalities with an estimated spatial resolution of better than 50 nm and a hypothetic temporal resolution on the order of picoseconds. In comparison, SQCM has therefore potential capabilities similar or better to those of scanning NV microscopy in terms of resistivity and temperature resolution, but operates in a lower temperature window much below 1 K inaccessible to most other techniques.

Put into context of quantum materials, SQCM will therefore be especially suited to study the microscopic properties of interaction driven quantum phase transitions in correlated phases of matter occurring at temperatures below 1 K, such as the superconductor-insulator-transition in magic angle twisted bilayer graphene \[3, 4\] or monolayer WTe\(_2\) \[31, 32\]. Through its potential to distinguish between different transport regimes, SCQM should be of value to, first, detect and study the transport characteristics of topologically protected boundary states in novel higher order topological insulator platforms \[11, 33\] as well as, second, to shed light on hydrodynamic transport and the underlying mechanisms, too \[34–36\]. Owing to the potential high temporal resolution, SQCM could help to shed light on charge carrier dynamics in meso- and nano-scale devices, such as non-equilibrium quasiparticles in superconducting films, which are known to deteriorate the performance of superconducting qubits \[37, 38\]. In a broader context, the noise spectroscopy based on qubit decoherence described above will also facilitate the dissipative transport characteristics of 2D quantum materials in non-local experiments using pure on-chip realizations (cf. Ref. \[19\]).

As far as the technical feasibility of SCQM is concerned, it is designed around established fabrication and measurement techniques for qubits and off-the-shelve technology for the scanning module and cryostat environment. The design and fabrication of superconducting qubits has experienced a tremendous development over the past decades \[39\], promising an optimized performance beyond reported Cooper pair box results of \(1/\gamma \approx 2 \mu s\) \[16\], for instance using a larger \(E_1/E_C\) ratio \[40\]. We note that gate charge drift, which changes the level splitting \(\Omega_0\) over the course of minutes and is a known weak spot of Cooper pair boxes, can be compensated for by feedback mechanisms and, thus, should not interfere with the SCQM operation. Moreover, low loss CPS resonators with internal quality factors \(Q_i > 10^5\) in the limit \(n_s \to 0\) can be reliably fabricated from different materials nowadays \[41\], helping to satisfy the condition \(g > \kappa\) in the more complex environment of a SCQM setup (\(\kappa = \omega_i/Q_i\)). Potential Purcell losses into the DC lines connecting the sample owing to the coupling capacitance \(C_C\) can be mitigated by appropriate on- and off-chip filtering \[42\].

Scanning operation will be readily implementable by using qPlus sensor technology and commercially available nanoprobers, suitable to operate at lowest temperatures \[43\]. Previous studies have already demonstrated the feasibility of integrating scanning probe setups into dilution refrigerator cryostats while maintaining lowest electron temperatures \[25, 44\]. Yet attention has to be paid to a proper thermalization and filtering of the DC lines needed for scanning operation \[45, 46\]. Regarding the tip-to-qubit fabrication, fusing the tip to a capacitor pad could be performed by means of micro soldering or focused ion beam assisted deposition, an approach commonly practiced in the context of the most recent scanning NV tip technology \[47\]. Alternatively, one can also envision more sophisticated all-on-chip solutions in the style of microfabricated tips already existing for scanning tunneling microscopy applications \[48\].

**Conclusion.** We have proposed SCQM as a new quantum sensing imaging modality to study the dissipative transport dynamics of new electronic phases in low-dimensional quantum materials. Backed up by model calculations, we demonstrate design concepts for local probe realizations based on the geometric capacitance forming between a sample and a tip, which is coupled to the charge qubit. We propose a tangible scheme for fast microwave read out of the qubit decoherence using standard homodyne techniques, facilitating fast scanning operation and realistic measurement times for SCQM. Our analytical and numerical analyses reveal the potential capability of SCQM to resolve temperature and resistivity changes of a sample as small as \(\Delta T \leq 0.1\) mK and \(\Delta \rho \leq 1 \cdot 10^4 \ \Omega \cdot \text{cm}\), respectively. SCQM, therefore overcomes existing limitations of superconducting qubits for quantum sensing applications and will be especially suited to study the microscopic mechanism of interaction driven quantum phase transitions in low-dimensional correlated phases of matter, visualize the local transport characteristics of novel topological materials as well as to investigate dissipative charge carrier dynamics in quantum materials with high spatial and temporal resolution.

**Acknowledgements** — It is our pleasure to acknowledge inspiring and educating discussions with Andrew Houck, Ali Yazdani, Andras Gyenis, Alex Place and Yonglong Xie. This work has been primarily supported by the Alexander-von-Humboldt foundation through a Feodor-Lynen postdoctoral fellowship. Additional support was provided by the
TABLE I: Scanning probe techniques for studying dissipative transport properties. Comparison between quantum sensing and related measurement techniques, which probe dissipative charge carrier transport with spatial $\Delta x$ and temporal $\Delta \tau$ resolution, respectively. Relevant properties and measurement quantities are listed.

| Technique       | Operating range (K) | Quantities (Resolution) | $\Delta x$ | $\Delta \tau$ |
|-----------------|---------------------|-------------------------|------------|--------------|
| Scanning NV     | 4 - 300             | $\sigma(1 \cdot 10^{-4} \Omega^{-1} \cdot cm^{-1})$ | 40 nm      | ps [21]      |
| tSOT [10]       | 0.3 - 10            | $T(\lesssim 1 \mu K)$    | $> 50$ nm  | -            |
| MIM [12]        | 2 - 300             | $\rho$                  | 100 nm     | -            |
| SCQM            | $\lesssim 0.1$      | $\rho(1 \cdot 10^{-5} \Omega \cdot cm)$ | $\lesssim 50$ nm | ps [21]      |

Office of Naval Research (ONR N00014-16-1-2391, ONR N00014-17-1-2784, ONR N00014-13-1-0661), ExxonMobil (EM09125.A1) and the Gordon and Betty Moore Foundation as part of the EPiQS initiative (GBMF4530). BJ acknowledges the hospitality of the Houck lab at Princeton University.

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FIG. 3: **Response the SCQM quantum sensor.** (a) Calculated response of the CQ to changes in the resistance and temperature of a sample with respect to the renormalized coupling capacitance $\eta$. Shown is the calculated change of the phase dip minimum, normalized to its maximum value at $\eta = 1$. 
(b) Calculated response of the CQ to temperature changes $\Delta T$ of a capacitively coupled sample using realistic setup parameters ($\eta = 0.1, \nu_\phi = 320\text{kHz}$) and different indicated values of the normalized sample resistance $\epsilon$. 
(c) Calculated response of the CQ to resistance changes $\Delta R$ of a capacitively coupled sample using realistic setup parameters ($\eta = 0.1, \nu_\phi = 320\text{MHz}$) and different indicated values of the environmental temperature $T$. 