APPLICATION BRIEF

Common-mode Artifacts in 2D Materials with Significant Contact Resistance

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Introduction

Two-dimensional materials are typically fabricated into Hall bar structures to study their electronic and magnetic properties. A four-probe longitudinal resistance measurement is effective at removing resistive contributions from contact or lead resistance, which is particularly important for low-resistance devices. However, even with a four-probe configuration, common-mode to differential-mode conversion can occur. In contrast with traditional common-mode rejection ratio (CMRR) issues, this spurious signal conversion occurs within the sample and does not depend on the amplifier CMRR. The spurious signal conversion becomes in-phase with the real measurement, preventing a lock-in user from using the phase shift as a diagnostic tool and making this effect difficult to detect. This can lead to measurement error and observations such as negative resistance, non-zero resistance in superconducting materials, or smeared quantum Hall effect data. Previous experiments have discussed these measurement artifacts in non-local voltage measurements.[1, 2] Here, we expand that discussion to conventional local four-probe measurements, present the conditions under which common-mode to differential-mode signal conversion becomes problematic, and ways to mitigate this issue using a balanced current source.

Example

Let’s examine the case shown in Figure 1. The channel, which is typically gated, has a resistance of 10 Ω. The contact resistance contributes roughly 10 to 20 kΩ, a value that is typical for 2D materials with one-dimensional contacts. While measuring 10 Ω with 10 to 20 kΩ of contact resistance might seem trivial at first, this measurement becomes extremely inaccurate with a traditional lock-in setup (Figure 1a). The traditional setup in Figure 1a includes a widely used single-ended AC current source, and a well-recognized lock-in amplifier with 10 MΩ of input impedance. In contrast, Figure 1b shows the M81-SSM setup which includes a balanced current source (BCS-10) and a high input impedance (>1 TΩ) voltmeter (VM-10). Performing the measurements with both setups yields the results shown in Table 1. Additionally, if the 20 kΩ is swapped with the 10 kΩ, the traditional setup measures near 20 μV with near zero phase shift, while the M81 setup measures the expected 10 μV. In the next section, we will discuss the results and the reason for the discrepancy.

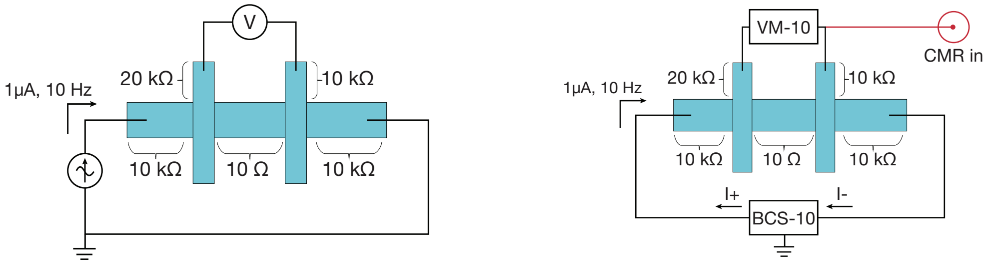

Figure 1a: Traditional setup

Figure 1b: M81-SSM setup

Figure 1a and 1b *Hall bar structure of a 10 Ω channel. The ~10 to 20 kΩ resistances can be a combination of contact resistance to the sample, in-line filters, cryogenic wiring, etc.*

Instruments	Expected voltage	Measured voltage (Vm)	Error
Traditional setup	10 μV	0.64 μV	93.6%
Lake Shore M81-SSM	10 μV	10.05 μV	0.5%

Table 1 *Experimental results of performing the measurements in Figure 1a and 1b using both a traditional setup and the M81-SSM.*

Circuit analysis

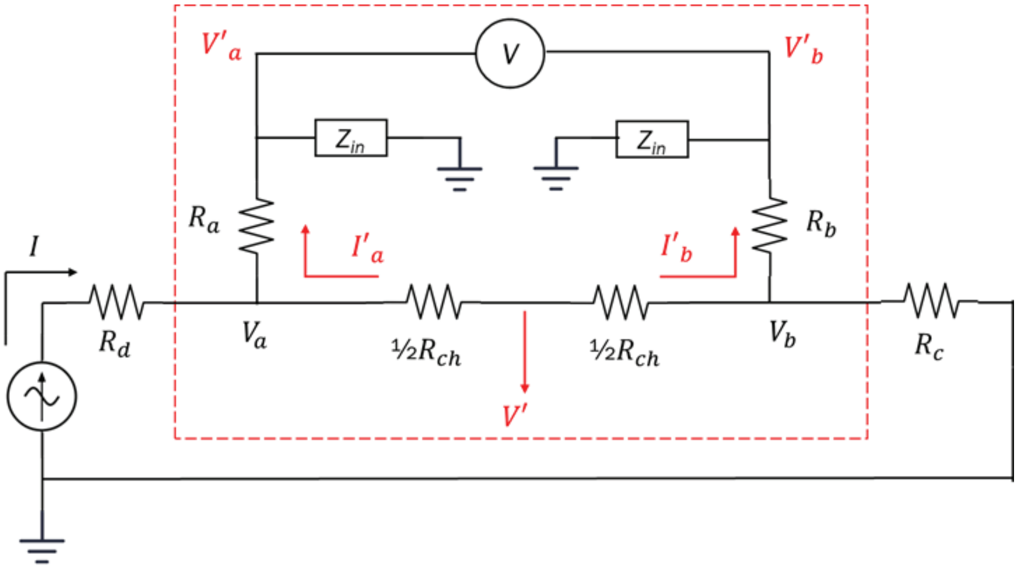

Figure 2 *Schematic of Figure 1 showing various contact resistances, and the input impedance to ground from both the voltmeter DC input impedance and the parasitic capacitance impedance from cabling and wiring to ground. The red-boxed circuit can be treated independently and the superposition theorem can be applied due to the assumptions:* $Z_{in} >> R_a \sim R_b \sim R_c \sim R_d >> R_{ch}$.

Let's analyze Figure 1 in circuit schematic form as shown in Figure 2. We have generalized the contact resistances as R_a, R_b, R_c, and R_d. The channel is split into two components of $\frac{1}{2}R_{ch}$ for ease of analysis. Lastly, an input impedance to ground is displayed to account for the voltmeter DC input impedance and capacitance impedance from cabling and wiring to ground.

In the following analysis, we will assume: $Z_{in} >> R_a \sim R_b \sim R_c \sim R_d >> R_{ch}$. The real voltage of interest is labeled as ΔV_{real}, and the artifact voltage (common-mode to differential-mode conversion) is labeled as $\Delta V_{artifact}$. The artifact voltage is resultant from the voltage V' generating currents I'_a and I'_b, which have two independent branches to ground. Each path is a voltage divider which depends on R_a, R_b, and Z_{in}. The assumptions stated earlier allow for the red-boxed schematic to be treated as an independent circuit and calculate $\Delta V_{artifact}$, and subsequently use the superposition theorem to calculate $\Delta V_{measured} = \Delta V_{real} + \Delta V_{artifact}$. We can derive a condition for when the effect of common-mode to differential-mode conversion voltage $\Delta V_{artifact}$ becomes significant relative to the signal of interest ΔV_{real}.

Expected signal	$\Delta V_{real} = V_a - V_b = IR_{ch}$
Common-mode to differential-mode artifact signal	$\Delta V_{artifact} = V'_a - V'_b = \left(\frac{Z_{in}}{Z_{in} + R_a} - \frac{Z_{in}}{Z_{in} + R_b}\right) V' \approx \left(\frac{R_b - R_a}{Z_{in}}\right) IR_c$ $\approx$
Measured signal	$\Delta V_{measured} = \Delta V_{real} + \Delta V_{artifact} \approx IR_{ch} + \left(\frac{R_b - R_a}{Z_{in}}\right) IR_c$
Percent error	$Error = \lvert\frac{\Delta V_{measured} - \Delta V_{real}}{\Delta V_{real}}\rvert \cdot 100\% \approx (\frac{R_b - R_a}{Z_{in}}) (\frac{R_c}{R_{ch}}) \cdot 100\%$

Discussion

Large input impedance relative to the sample resistance typically results in negligence of the effects of contact resistance in the voltage probes. However, a combination of significant common-mode, differences in the resistances to inputs A and B, and small signals of interest can result in the neglected current leakages to inputs A and B creating voltage differentials similar to what is intended to be measured. The common-mode converts to an in-phase differential-mode within the sample due to the small differences in leakage currents.

To reduce the error, the following methods are helpful. (1) a lock-in or pre-amp with high input impedance, (2) lower frequency and reduced cable capacitance, (3) a balanced current source with feedback for common-mode removal. It is worth noting that even with a very large DC input impedance voltmeter, cable/wiring/filter capacitance of only ~1.5 nF is enough to create an impedance to ground of 10 MΩ at 10 Hz. Therefore, the best method is to balance the current such that V' is minimized (independently of the current I). The M81-SSM BCS-10 can provide a differential current based on a feedback loop such that a selected node in the circuit is driven to zero volts. In Figure 1, the BCS-10 CMR IN connection is connected to the B terminal of a voltmeter, reducing this node near zero volts, and consequently minimizing the common-mode to differential-mode conversion.

Conclusion

Many transport experiments on 2D materials struggle with large contact resistance. We showed that contact resistance can create spurious signal conversions from common-mode by analyzing a 10 Ω channel surrounded with 10 to 20 kΩ contacts in a traditional lock-in setup. This spurious common-mode to differential-mode signal conversion is not removed by using a four-probe resistance configuration, and is in-phase with the real signal of interest, making it difficult to detect. We derived an expression to check when the spurious signal becomes significant relative to the real signal in terms of: contact resistances, channel resistance, and impedance to ground from the voltmeter input impedance and parasitic capacitance. Lastly, we demonstrated that the features of the M81-SSM, a balanced current source with a high input impedance voltmeter, are the ideal solution to prevent the spurious signal generation from contact resistances.

References

1. Sui, M., Chen, G., Ma, L. et al. Gate-tunable topological valley transport in bilayer graphene. Nature Phys 11, 1027 – 1031 (2015).
2. Shimazaki, Y., Yamamoto, M., Borzenets, I. et al. Generation and detection of pure valley current by electrically induced Berry curvature in bilayer graphene. Nature Phys 11, 1032 – 1036 (2015).