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# Magnetic noise measurements using cross-correlated Hall sensor arrays

G. Jung[a)]
*Department of Physics, Ben Gurion University of the Negev, P.O. Box 653, 84105 Beer-Sheva and Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

M. Ocio
*Service de Physique de l'Etat Condensé, C.E. Saclay, Orme Des Merisiers, 91191 Gif Sur Yvette, Cedex, France*

Y. Paltiel, H. Shtrikman, and E. Zeldov
*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

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An experimental technique for measuring magnetic fluctuations by means of a double-layer Hall sensor array is described. The technique relies on cross-correlating Hall signals from two independent sensors positioned one above the other in two separate two-dimensional-electron-gas layers of a GaAs/AlGaAs heterostructure. The effectiveness of the technique is demonstrated by a reduction of the magnitude of the background noise floor of the correlated sensors with respect to the noise level of the best single sensor.
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Dynamic properties of the magnetic flux lines in type-II superconductors have been the subject of intense theoretical and experimental activities for many years. Discovery of new high-T$_c$ superconducting (HTSC) materials enhanced the range of available experimental parameters and opened new perspectives for studies of the vortex matter dynamics. The short coherence length of HTSC cuprates combined with strong anisotropy, relatively weak pinning, and high temperature of operation, leads to pronounced manifestations of flux and voltage noise in the experiments.[1,2] Although the noise component of the experimental signal is generally regarded as an unwanted disturbance, it can constitute a precious source of information about the system under investigation. Therefore, there is a growing interest towards understanding the physical mechanisms governing the statistical mechanics of the vortex matter, and in particular the magnetic flux fluctuations associated with the vortex matter phase transitions, instabilities of the critical state, or nucleation of spontaneous vortex-antivorex pairs in two-dimensional systems.[1–7]

In a typical experimental arrangement the flux noise is studied by measuring fluctuations of the magnetic flux threading the active area of the flux sensing device situated above the sample surface. Superconducting quantum interference devices (SQUID) are known to be the most sensitive flux measuring devices and are well suited for low temperature operation. However, a problem arises when the temperature dependence of the magnetic noise needs to be investigated. Proper operation of a SQUID sensor requires maintaining the constituting Josephson junctions at a constant temperature, usually 4.2 K for commercial low temperature devices. This enforces operation with an external pickup loop that has to be well thermally insulated from the investigated sample. The required thermal insulation significantly increases the distance between the sample and the pickup coil leading to a pronounced decrease of the coupling between the fluctuating magnetic signal and the sensor. Early experiments on flux noise have shown that the noise intensity decays rapidly with increasing separation between the pickup coil and the sample surface.[8] Recent theoretical study shows that in the limit $d \ll r$, the intensity of the fluctuations decays as the third power of the distance $d$ between the sample surface and the pickup loop of the linear dimension $r$.[9]

Miniature Hall probes based on two-dimensional-electron-gas (2DEG) structures offer a challenging alternative to the SQUID. Hall sensors operate well in a changing low temperature environment. The Hall coefficient in 2DEG heterostructures is practically temperature independent below 100 K. With improving technology the sensitivity of the 2DEG Hall sensors, typically 0.1–0.3 Ω/G, starts to be comparable to that of commercial HTSC SQUID sensors, while providing significantly better spatial resolution, for a recent critical review see Ref. 10. This feature is of particular importance for local noise measurements which enable one to resolve the spatial structure of the fluctuations. Local noise measurements start to be of great interest in connection with the flux fluctuations arising due to plasticity and melting of the vortex lattice.[11–13]

The major draw back of the 2DEG Hall sensors as noise measuring devices is their relatively high resistance $R_V$ seen by the Hall voltage measuring circuit, even at low temperatures. The high self-resistance results in high thermal noise $4k_BTR_V\Delta f$ that dominates the signal-to-noise ratio of the 2DEG Hall sensors.

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{I_b \rho_H B}{\sqrt{4k_BTR_V\Delta f}}, \tag{1}$$

where $\Delta f$ is the experimental bandwidth, $k_B$ is the Boltzman

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[a)] Also at: Instytut Fizyki PAN, Al. Lotników 32, PL 02-668 Warszawa, Poland; electronic mail: jung@bgumail.bgu.ac.il

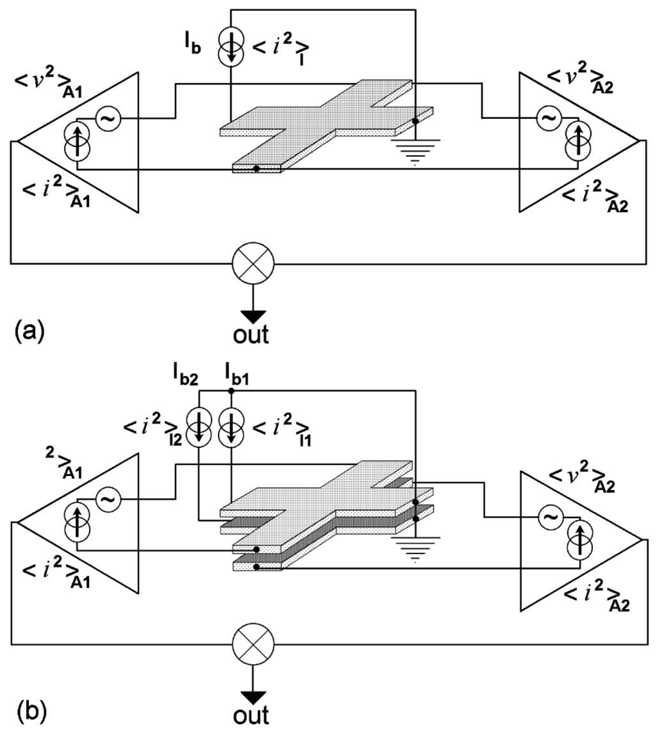

FIG. 1. (a) Classical cross-correlation arrangement. The Hall probe signal is read simultaneously by two independent amplifier channels. The cross-correlated output signal contains the thermal noise of the probe and the correlated noise components resulting from injection of the input noise current of both amplifiers to the same sensor. (b) Cross-correlation of two independent Hall sensors eliminates drawbacks of the classical configuration. Here, all noise components are uncorrelated and eliminated from the output.

constant, $T$ is the temperature, $I_b$ is the dc current bias of the probe, $\rho_H$ is the Hall probe coefficient, and $B$ is the measured magnetic induction.

In the typical experimental conditions the Hall probe is biased by a dc current source which can contribute a current noise component $\langle i^2\rangle_I$ to the bias $I_b$. Moreover, the probe is connected to the voltage amplifier in the Hall signal measuring chain. The S/N ratio of the Hall probe is, therefore, further deteriorated by its far from optimum noise matching conditions to the voltage preamplifier. Using the preamplifier with the input voltage noise $\langle v^2\rangle_A$ and the input current noise $\langle i^2\rangle_A$, the experimentally available signal-to-noise ratio is reduced to

$$\begin{aligned} \mathrm{S/N} &= \frac{I_b\rho_H B}{\sqrt{\langle V^2\rangle}} \\ &= \frac{I_b\rho_H B}{\sqrt{4k_BTR_V\Delta f+\rho_H^2B^2\langle i^2\rangle_I+\langle v^2\rangle_A+R_V^2\langle i^2\rangle_A}}, \end{aligned} \quad (2)$$

where all but the thermal noise term in the total input noise $\langle V^2\rangle$ contain $1/f$-like contributions. One can note that the thermal noise increases like $R_V$, while the term due to current noise contributed by the amplifier increases like $R_V^2$, and thus can dominate for large values of $R_V$.

The voltage noise added by the preamplifier chain can be reduced by applying the cross-correlation technique.[14–16] In the classical cross-correlation scheme, see Fig. 1(a), the output signal of the Hall sensor would be delivered to two independent preamplifiers. The cross correlation of the amplifiers outputs eliminates the uncorrelated $\langle v^2\rangle_{A1}$ and $\langle v^2\rangle_{A2}$ noise components and leads to the reduction of the total noise. Averaging M cross-correlated records will result in a noise reduction by a factor $\sqrt{M}$. This improvement however, leaves us with thermal and current noise components. Moreover, as it follows from Fig. 1(a), the input noise currents of both amplifiers add up in the probe. As a result, the total noise becomes

$$\langle V^2\rangle=4k_BTR_V\Delta f+\rho_H^2B^2\langle i^2\rangle_I+R_V^2[\langle i^2\rangle_{A1}+\langle I^2\rangle_{A2}]. \quad (3)$$

The additive amplifier input current noise terms may actually deteriorate cross-correlated S/N ratio to such extent that it becomes less favorable than the S/N ratio of a single channel. Consider for example, a pair of good quality amplifiers with input rms noise voltage of $1\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and rms noise current of $1\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$. It follows from (3) that the cross correlation would lead to a deterioration of the S/N ratio as soon as the probe resistance $R_V$ becomes larger than 700 $\Omega$.

Fortunately, we can profit from the fact that the Hall probe is not the actual source of the signal of interest but only a transducer converting the magnetic induction fluctuations into a voltage signal. We can, therefore, use two independent probes to sense the same magnetic induction signal and cross correlate their output voltages by processing them in two independent channels, as illustrated in Fig. 1(b). In the modified two-probe cross-correlation arrangement all noise components of the total noise $\langle V^2\rangle$ are uncorrelated and to a large extend, depending only on the number of averages $M$ performed in the cross-correlating procedures, eliminated from the correlated signal. On the other hand, the fluctuations of the magnetic flux that originate in the underlying sample are strongly correlated, leading to a significant improvement of the final S/N ratio. For large $M$ the S/N ratio will be limited only by residual correlation between the Hall probes. In the experimental reality, noise signals in two independent Hall channels may couple and get correlated via stray inductances and capacitances. Such coupling can be reduced by a careful design of the experimental setup. Nevertheless, the two-probe arrangement has a built-in source of intrinsic residual correlations which cannot be reduced. Namely, the noise current circulating in one probe induces a fluctuating magnetic field which is sensed by the other probe.

In this letter we report on our successful attempt of reducing the noise in 2DEG Hall sensors by cross-correlating signals from two independent sensors, placed closely one above the other, in a double-layer 2DEG heterostructure, similar to the recently developed two-layer Hall array gradiometer.[17]

The double-layer Hall sensor structures were fabricated from AlGaAs/GaAs heterostructures consisting of two parallel 2DEG layers grown on undoped semi-insulating (100) oriented GaAs substrates in a molecular beam epitaxy system under conventional growth conditions. The final shape of the device, consisting of two layers of eleven $10\times100\,\mu\mathrm{m}^2$ Hall sensors connected in series, was defined in subsequent steps of etching mesa structures end evaporating ohmic contacts to both layers.

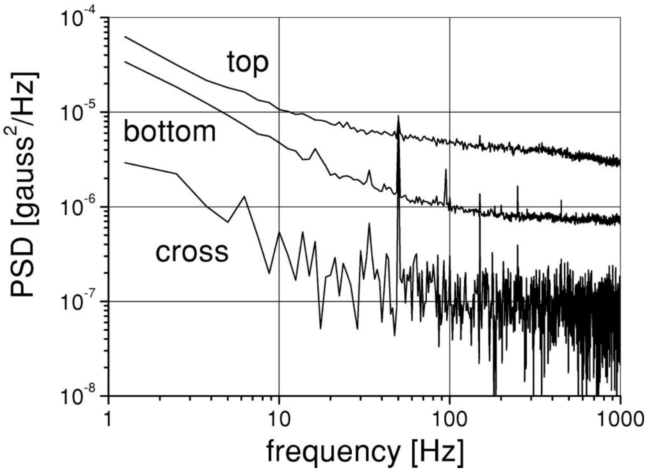

FIG. 2. Background noise spectra of the upper and lower layer Hall sensor and the reduced background noise spectrum obtained by cross-correlating signals from two independent sensors. Temperature of the experiment 40 K, dc bias current $I_b = 50\ \mu A$, number of averages $M = 500$.

The device was tested in a low noise variable temperature cryostat equipped with an external $\mu$-metal magnetic screen and an internal superconducting screen. The current to the Hall arrays was supplied by two separate battery powered current supplies. The Hall voltages were amplified by two independent homemade low noise preamplifiers placed directly on the cryostat top, and processed by a two-channel cross correlator and spectrum analyzer. The evaluated sensitivity of double layer Hall sensors to the applied magnetic field at temperatures below 100 K was close to 0.2 Ω/G, similar to that of the single layer sensors.[11]

Figure 2 illustrates the feasibility and potentiality of the proposed cross-correlation technique. Spectra labeled ''top'' and ''bottom'' are the background noise spectra of the individual Hall sensors from the top and bottom 2DEG layer of the double layer Hall structure, respectively. The cross correlation of the top and bottom layer Hall signals, after 500 averages, produces the background noise spectrum, labeled ''cross'' in Fig. 2, which is reduced by an order of magnitude with respect to the background noise level of the better individual sensor. In the white noise region of the spectrum the final noise floor of our measuring arrangement is of the order of $10^{-7}\ G^2/Hz$ at 40 K and $I_b = 50\ \mu A$.

The experimentally observed reduction of the cross-correlated background noise level is weaker than the theoretically predicted $\sqrt{M}$ factor due to residual correlation between the probes. In a number of tests we have found that the strength of the residual correlations increases with decreasing frequency. For example, the cross-correlated background noise after $M = 10^4$ averages was reduced, with respect to the single channel noise floor, more than 80 times at 5 kHz, but only a few times at 500 Hz, and left almost unchanged at 5 Hz. This is most likely due to magnetic coupling of the amplifiers current noise with $1/f$ component.

It has to be underlined that in order to keep the residual correlations low, both sensors have to be of the highest quality. We have observed that appearance of a random telegraph noise component in any of the cross-correlated sensors leads to a significant increase of the cross-correlated background noise level. In most cases, the appearance of telegraph noise brings the cross-correlated noise floor close to the background noise of the better sensor, thus canceling any advantage of the cross-correlation technique. Unfortunately, in a system of two closely placed 2DEG active layers it is not easy to avoid parasitic effects due to active surface traps leading to the manifestations of telegraph fluctuations resulting from trapping and releasing of charge carriers and modulating the conductivity of the 2DEG layers. Thus, the fabrication of good quality double layer 2DEG Hall sensors, suitable for the cross-correlation measurements, remains a hard technological challenge.

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