Magnetic noise measurements using cross-correlated Hall sensor arrays

G. Jung\textsuperscript{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

(Received 3 August 2000; accepted for publication 21 November 2000)

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. © 2001 American Institute of Physics.

[DOI: 10.1063/1.1340866]

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\textsubscript{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.\textsuperscript{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-antivortex pairs in two-dimensional systems.\textsuperscript{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 (SQUIDs) 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 environment. The Hall coefficient in 2DEG is typically practical temperature independent below 100 K. With improving technology the sensitivity of the 2DEG Hall sensors, typically 0.1–0.3 \textOmega/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.\textsuperscript{11–13}

The major draw back of the 2DEG Hall sensors as noise measuring devices is their relatively high resistance \textit{R}_V seen by the Hall voltage measuring circuit, even at low temperatures. The high self-resistance results in high thermal noise by the Hall voltage measuring circuit, even at low temperatures. The high self-resistance results in high thermal noise 4\textit{k}_B\textit{T}_V\Delta\textit{f} that dominates the signal-to-noise ratio of the 2DEG Hall sensors.

\begin{equation}
\frac{S}{N} = \frac{I_b\rho_B B}{\sqrt{4k_B T_V \Delta f}},
\end{equation}

where \Delta\textit{f} is the experimental bandwidth, \textit{k}_B is the Boltzmann
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

\[
\langle V^2 \rangle = 4k_B T R_V \Delta f + \rho_B^2 B^2 \langle i^2 \rangle_f + R_V^2 \langle i^2 \rangle_A + \langle I^2 \rangle_{A2}. \tag{3}
\]

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 nV/\( \sqrt{\text{Hz}} \) and rms noise current of 1 pA/\( \sqrt{\text{Hz}} \). 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 \( \times 100 \mu \text{m}^2 \) Hall sensors connected in series, was defined in subsequent steps of etching mesa structures end evaporating ohmic contacts to both layers.
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.

This work was supported by the Israeli Science Foundation founded by the Israeli Academy of Sciences and Humanities-Center of Excellence Program and by the German-Israeli Foundation G.I.F.

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 $10^{-7} \text{G}^2/\text{Hz}$ at 40 K and $I_b = 50 \mu \text{A}$. 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

![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 $I_b = 50 \mu \text{A}$, number of averages $M = 500$.](image)