Hall cross size scaling and its application
to measurements on nanometer-size iron particle arrays

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Hall crosses were used to measure the magnetic properties of arrays of ferromagnetic, nanometer-scale iron particles. The arrays typically consist of several hundred particles of 9 – 20 nm in diameter. It is shown that the sensitivity of the measurements can be improved by matching the areas of the Hall cross and the array grown onto it by at least an order of magnitude. We predict that single particles of diameter as small as 10 nm can be measured if grown onto a Hall cross of appropriate size.

There continues to be great interest in small magnetic particles and well-arranged particle arrays. This research is driven by the demand for an understanding of the physics and potential application of such particle arrays as advanced magnetic storage media. The challenge, however, is not only in the fabrication of such particles but also in the measurement of magnetic properties of small volumes. One obvious choice for the latter is the use of dc micro-SQUIDs with which excellent experiments have been performed. These measurements, however, are ordinarily restricted to low temperatures. MFM investigations can provide spatially resolved information on the magnetic state of the particles and are of special merit if conducted in applied fields. They suffer, however, in that quantitative results are difficult to extract. Hall magnetometry has the advantages of being versatile and comparatively simple in set-up. Furthermore, temperature and magnetic field strength are not restricted. Applications range from flux characterization in superconductors to scanning Hall probes. The sensitivity and the accessible temperature range depend on the material used for fashioning the device.

Hall gradiometry has been used to measure the magnetization of small particle arrays. Here, nanometer-scale particles of regular shape and arrangement were grown onto III-V semiconductor Hall crosses. This allowed magnetization measurements over a broad temperature range (up to 100 K). Moreover, enhanced interactions between the particles have been studied. Thus, important issues in data storage applications (superparamagnetic limit, interactions) can be addressed.

In this letter, we show that the sensitivity of Hall measurements can be significantly increased by matching the sizes of the active area of the Hall cross and of the particle array. Hall voltages calculated from the magnetic stray field of the particles are compared to measured values. We predict that single nanometer-size particles can be measured by appropriately small Hall crosses. The results can be applied to any magnetic object to be measured by Hall magnetometry.

Iron particle arrays were grown by a combination of chemical vapor deposition (CVD) and scanning tunneling microscopy (STM). This method has successfully been used to fabricate particles from 9 to 20 nm in diameter, 50 - 250 nm in height and with interparticle distances down to 80 nm onto gold and permalloy. During the growth process, vaporized iron pentacarbonyl is introduced into the STM chamber and decomposed within the electric field of the biased tip. For negative tip bias voltage, the iron deposit grows on the sample surface. At the same time, the tip is retracted, keeping the distance between the deposit’s top and the tip constant by maintaining a constant tunneling current of 50 pA. When the deposit has grown to the desired height (measured via the tip retraction) the tip is retracted completely and moved to the next location on the sample surface where the process is repeated to form the particle array. An advantage of this fabrication procedure is that the particles’ height and location (with respect to each other and to features on the sample surface) can easily be controlled by steering the STM-tip. This feature becomes even more important as the size of the Hall crosses is decreased. It should be

FIG. 1. SEM picture of an array of 420 particles grown onto a Hall cross. The etched Hall cross of about $3.2 \times 2.8 \mu m^2$ is clearly visible. The image shows an area of $4.5 \times 4.5 \mu m^2$. 

two-dimensional electron system (2DES), n step, the stray field (i.e., its netic stray field of the particles. A two-step procedure of a typical array is presented in Fig. 1. which the arrays were directly grown. The SEM image thin gate was deposited onto the Hall bars, on top of which the arrays were directly grown. The SEM image of a typical array is presented in Fig. 1.

The measured Hall voltage originates from the magnetic stray field of the particles. A two-step procedure was developed to analyze the Hall voltage: In a first step, the stray field (i.e., its z-component perpendicular to the plane of the 2DES) of each particle at the depth at which the 2DES located is calculated analytically. The contributions of each particle are then summed up to get the local z-component of the stray field emanating from the whole array. In a second step, the Hall voltage produced by this magnetic stray field within the active area of the Hall cross is calculated. The parameters needed are either known from the fabrication process of the 2DES or can easily be measured. With all other parameters known, the procedure can be used to estimate the mean diameter of the particle iron core from the measured Hall voltage.

In order to optimize the sensitivity of the Hall device the efficiency of the conversion of the particles’ stray field into Hall voltage, i.e. the second step, has to be evaluated. Properties most easily controlled in the fabrication process are the relative size and location of the array with respect to the Hall cross (we do not intend to discuss the properties of different 2DES materials in this letter). In Fig. 2 (circles) the calculated, relative Hall voltage produced by a typical test array is presented if the array were grown onto Hall crosses of different sizes (all other parameters remained unchanged including the drive current). Obviously, the array’s stray field is most effectively converted into Hall voltage if the Hall cross size does not exceed the array size. In this case, all electrons in the active area of the Hall cross are influenced by the stray field and the stray field influences the potential over the complete width of the voltage leg. Compared to arrays fabricated earlier, one should be able to increase the sensitivity by an order of magnitude just by matching the sizes of array and Hall cross. The calculations were performed assuming aligned centers of array and Hall cross (filled circles). If the Hall cross is smaller than the array, only that corresponding portion of the array causes a Hall voltage. The total stray field at the center of an array is, however, slightly smaller than at an edge or even at a corner of the array. This effect which has been noted before can be explained by the fact that the closest (and therefore most effective) fluxlines from center particles form closed lines within the active area of the Hall cross and do not contribute to the Hall voltage. Hence, the Hall response is reduced at the array’s center. In contrast, for a small Hall cross located with its edge underneath the corresponding edge of the array, the Hall response is slightly increased.

Another parameter that could somewhat be influenced is the separation in z-direction between the 2DES layer and the particles (e.g. via the gate thickness). This, however, is expected to have only a minor influence on the Hall response (Fig. 2 crosses and upper scale).

To make use of the predicted increase in sensitivity we prepared Hall crosses of approximately 3 × 3 μm² in size (cf. Fig. 1). As described before, arrays of several hundred iron particles with interparticle distances of 150 nm were then grown onto these Hall crosses. The dimensions were chosen to match the size of the Hall crosses to be grown onto and to approximate arrays fabricated earlier. This permits direct comparison of the measured Hall voltages. Magnetic measurements were performed from 10 – 100 K and for different angles of the applied field. Due to their elongated shape (aspect ratio of approx. 5:1) the particles possess a large shape anisotropy making their long axis an easy magnetization direction (EMD) along z. A mean particle switching field of \( H_{sw} = 160 \text{ mT} \) for fields applied parallel to the EMD (Fig. 3, top panel) was observed. Apart from the typical switching field distribution (about 30 mT) there was a small portion of particles with a distinguishable higher \( H_{sw} \) of about 230 mT as indicated by “bumps” in the corresponding parts of the magnetization curves. Such a twofold switching field distribution may be caused by a distribution of the magnetic core diameter of the particles. It seems more likely, however, that the majority of the particles consisted of more than one grain. Therefore,
they have a smaller switching field than single crystalline particles. Such structural differences would naturally account for distinguishable $H_{\text{sw}}$-values.

For fields perpendicular to the EMD, the magnetization behavior was controlled by reversible rotation (Fig. 3, lower panel). For increasing fields strength, the particle magnetization rotated toward the field direction, i.e., toward an orientation perpendicular to the z-direction. Thus, a decreasing Hall voltage is measured. For intermediate angle (shown in the center panel of Fig. 3) both reversible rotation and switching contribute to the overall magnetization behavior: the former ends to a small decrease of the z-component of the magnetization (visible at fields below about 130 mT) whereas the latter dominates around 200 mT. An estimate of the mean value of the shape anisotropy constant from the reversible part of this curve (based on the Stoner-Wohlfarth model) yielded $K_S \approx 0.3$ MJm$^{-3}$. This value is about 40% of the number expected from the particles’ shape. This again indicates that most of the particles are polycrystalline. The peculiar shape of the curve measured at 90° can then be explained by a distribution of $K_S$-values with maximum $K_S$-values as high as 0.45 MJm$^{-3}$.

The Hall voltages measured for 0° and 60° exceeded those measured earlier by more than an order of magnitude (after adjusting for changed experimental conditions, e.g., drive current, carrier concentration) in good agreement with our predictions. At zero field, the measured Hall voltage should not depend on the orientation of the applied field if all magnetizations of the individual particles point in the same direction. Obviously, this condition was not fulfilled for curves measured for 90°. In fact, for fields decreasing from a value well above the anisotropy field the particle magnetization could rotate toward either direction along the EMD. From the 0° and 60°-curves a mean particle core diameter of 17 nm was estimated (particles were grown 80 nm in height).

We emphasize that the resulting Hall voltage does not substantially depend on the absolute size of the array or the Hall cross—as long as they match. In the present experiment the noise of the Hall voltage was measured to be 0.04 $\mu$V/$\sqrt{\text{Hz}}$ at 30 K and zero field and increased to about 0.07 $\mu$V/$\sqrt{\text{Hz}}$ at 100 K and 1.0 T. We predict a Hall voltage of $\approx 0.24 \mu$V for a single particle of 10 nm diameter grown onto a 400 $\times$ 400 nm$^2$ Hall cross (experimental conditions as for the measurements in Fig. 3: no depletion effects of the 2DES were taken into consideration). This voltage would exceed the highest noise level by a factor of 5. Hence, we expect to be able to measure any number of particles, from a single particle to a few particles up to arrays of several hundred particles, by growing them on Hall crosses of appropriate size. Here, STM assisted growth appears to be the perfect tool.

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FIG. 3. Hall voltages of an array of 462 particles with a 17 nm diameter measured at 30 K. The field was applied at different angles (shown are 0°, 60°, 90°) with respect to the particles’ long axis, i.e. their easy magnetization direction.

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