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June 20, 2019

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***Abstract*—Noise measurements are supposed to be a powerful tool to study the dynamical properties of a driven lattice of magnetic skyrmions. In analogy to the properties of driven superconducting vortices, broad-band and narrow band noise is expected to probe the microscopic pinning potential and low-frequency dynamics of the skyrmion lattice. We present first measurements of fluctuation spectroscopy on epitaxial grown MnSi thin film samples, which are expected to show a larger amplitude of fluctuations due to their strongly reduced volume as compared to bulk systems and enhanced absolute resistance values. We observe generic $1/f$-type noise, however with only a weak temperature dependence and no signatures of a magnetic skyrmion phase, which may be explained by electronic inhomogeneities or the absence of a well-defined skyrmionic phase in these samples subject to subtrate-induced strain. Upon approaching the helical magnetically ordered phase in zero field, we observe an enhancement of the $1/f$-type fluctuations and two-level switching of a characteristic energy, possibly related to the switching of magnetic grains/clusters.**

***Index Terms*—fluctuation spectroscopy, thin films, skyrmions, 1/f-noise**

Motivation

Magnetic skyrmions are topologically protected chiral spin textures with novel characteristics suitable for encoding data in memory applications. The formation of magnetic skyrmions is often facilitated by the presence of a strong Dzyaloshinskii-Moriya interaction, which prefers a non-collinear spin orientation between adjacent magnetic moments. Since their experimental discovery in the last decade [1]–[3], magnetic skyrmions as a new type of magnetic order related to the field of topology have attracted great interest in condensed-matter physics. Manipulating magnetic skyrmions, individually or moving coherently in a lattice, is considered a promising scheme to resolve the limitations of state-of-the-art spintronics applications [1], [4]–[6].

Bulk single-crystals of the cubic helimagnetic B20 compound MnSi exhibit intrinsic skyrmions due to a crystal structure favoring spin-orbit coupling and lacking inversion symmetry [7]. In this system, the early-reported field-induced magnetic A-phase does represent an ordered magnetic skyrmion lattice [1]. Whereas the magnetic properties and phase diagram of bulk MnSi is investigated intensively and understood quite well, and where the signature of the skyrmion phase has been observed by various techniques, as e.g., neutron scattering [1], topological Hall effect [3] and many more, the skyrmionic behaviour in thin films of MnSi still remains rather unclear, see [8] and references therein.

As a potentially powerful probe to investigate the skyrmion dynamics, we employ fluctuation (noise) spectroscopy aiming to detect intrinsic $1/f$-type fluctuations. In analogy to what is observed for the driven superconducting vortex lattice [9]–[11], one expects to see pronounced signatures of the pinning/depinning transition of the skyrmion lattice [4] in the noise magntitude as a function of the current density. Furthermore, again similar to the findings for the superconducting vortex lattice, broad-band noise may be detected when the skyrmion lattice starts moving and narrow-band noise when the skyrmion velocity increases. This may allow to estimate pinning potentials, the skyrmion velocities and the characteristic energies of the dynamical processes.

In bulk MnSi, the large sample volume and low absolute impedances render the observation of 1/f noise rather difficult. Therefore, we have chosen to attempt such measurements on MnSi thin films trying to resolve changes in the low-frequency fluctuation properties upon entering the different magnetically ordered phases. Thin film samples can be patterned by standard lithography techniques, therefore allowing for well-defined geometries. MnSi enters a helical ordered ferromagnetic state when cooling down the samples in zero magnetic field. The transition temperature of $T_C \sim 29 - 30\,\mathrm{K}$ in bulk single crystals is shifted in thin-film samples to considerably higher temperatures, which is attributed to the effect of the substrate-induced strain of the thin film [13]. At finite fields between $B \sim 0.1\,\mathrm{T}$ and $0.2\,\mathrm{T}$, and between $T \sim 28\,\mathrm{K}$ and $29\,\mathrm{K}$, the skyrmion phase is seen in bulk samples, whereas it becomes considerably wider in the temperature-magnetic field phase diagram for thin films, see [12].

Sample and Experiment

The epitaxially-grown thin films of MnSi were prepared in ultra-high vacuum by molecular beam epitaxy with a base pressure of below 5×10^{-11} mbar as described previously [8], [14]. The samples are single-phase MnSi and the surface roughness is well below 3 nm. A detailed description of sample preparation, surface analysis and a characterization of the (magneto)transport properties is presented in [8].
The samples were micro-structured by electron beam lithography [14] allowing to perform well-defined resistance measurements. The structures are $10\,\mu\mathrm{m}$ wide, have a thickness of $30\,\mathrm{nm}$ and the voltage leads have a distance of $70\,\mu\mathrm{m}$. Electrical contacts have been made by silver epoxy and were found to be in the ohmic regime for the current densities applied. Temperature dependent resistance and resistance noise measurements have been performed in a continuous helium-flow cryostat with variable temperature insert using a standard four-point AC technique and a lock-in amplifier. With a maximum applied current of $I = 100\,\mu\mathrm{A}$ and the proportions described above current densities of up to $j = 3.3 \times 10^{-8}\,\mathrm{A/m^2}$ have been achieved. The AC voltage is applied to a voltage divider circuit with a limiting resistor much larger than the sample resistance. After pre-amplification, the resulting voltage signal is processed by the lock-in and the voltage noise power spectral density (PSD) of the emerging fluctuations is calculated by a spectrum analyzer [15].

Results and Discussion

Fig. 1 shows the zero-field resistivity of a representative thin-film MnSi sample exhibiting an overall behaviour similar to results previous reported [8], [16]. In the whole measured temperature range the sample is in the metallic regime (see below for a discussion of the resistivity maximum at $\sim 225\,\mathrm{K}$) with an anomaly occurring at entering the helical state. Here the slope of the resistivity curve shows a pronounced kink at around $T_C \sim 46\,\mathrm{K}$ upon entering the magnetic phase, the temperature of which is significantly shifted with respect to bulk MnSi, see for comparison the suggested phase diagram for thin-film samples in [12]. This is caused by the tensile strain/effective negative pressure induced in MnSi thin films by the lattice mismatch with the Si substrate [8].
With increasing temperature, the resistivity increases until $\rho(T)$ shows a maximum at around 225 K, above which the resistivity decreases upon increasing the temperature up to 300 K. This behavior has been seen before and has been analyzed in terms of parallel conductivity through the Si substrate and a Schottky barrier at the interface between the contact pads and the Si wafer [8]. For the noise measurements discussed below, we discuss only the low-temperature behavior which remains unaffected by the parallel conduction path.
The inset of Fig. 1 shows a typical noise spectra, i.e. the voltage noise power spectral density taken at $T = 10\,\mathrm{K}$, zero magnetic field and different applied currents. The spectra exhibit a typical $1/f$-type behavior and, as required, the spectrum for vanishing applied current becomes flat ('white'). Furthermore, the noise magnitude shows the expected scaling $S_V \propto I^2$ according to Hooge's empirical law [17]

$$S_V(f) = \gamma_H \cdot \frac{V^2}{n\Omega f}, \tag{1}$$

where the Hooge parameter γ_H is a material's parameter, n the carrier concentration and Ω the 'noisy' volume of the sample. Initially, the Hooge parameter was thought to be constant and of order $10^{-3} - 10^{-2}$ for various semiconducting materials. Later, however, experiments revealed that Hooges constant actually ranges from 10^6 to 10^7 for different classes of materials, and is also temperature dependent. Despite all arguments against a physical meaning of Hooges equation, it remains a convenient way to compare the noise level of different systems [18]. With the dimensions of our thin film, the current density applied in the temperature-dependent measurements discussed below and an estimated charge carrier density of $n = 1.7 \times 10^{22}\,\mathrm{cm^{-3}}$ [8], we estimate a Hooge parameter of $\gamma_H \sim 3 \times 10^{-1}$.

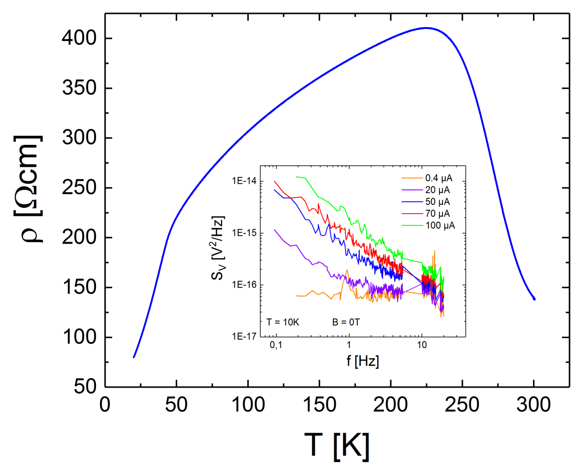

Fig. 1. Temperature dependence of the resistivity, $\rho(T)$, of a MnSi thin film on Si substrate, see text for details. Inset: Current dependence of the voltage noise power spectral density $S_V(f)$ at $T = 10\,\mathrm{K}$ and $B = 0$. The spectra show typical $1/f$-type behaviour, merging in a 'white' spectrum for vanishing current, and scaling $S_V \propto I^2$.

In Fig. 2 we show (a) the normalized resistance noise PSD, $S_R/R^2(T)$ evaluated at $f = 1\,\mathrm{Hz}$ and (b) the frequency exponent $\alpha(T)$ at different magnetic fields $B = 0\,\mathrm{T}$ and $B = 0.2\,\mathrm{T}$. Zero-field data are shown up to 200 K. In a wide range of temperatures, both the noise magnitude and the frequency exponent are essentially flat and independent of the external magnetic field. Besides a slight increase of $S_R/R^2(T)$ below about 20 K accompanied by a shift of spectral weight to higher frequencies observed for both the zero field and $B = 0.2\,\mathrm{T}$ curves, no anomalous behavior in the magnetic phase is observed. We have not seen a dependence of the fluctuation properties on the driving current density. In particular, we have not observed any changes in the noise behavior upon varying the magnetic field below T_C, i.e. we have not seen a signature indicating a skyrmion phase. This likely is related to the fact that the very existence of a skyrmion lattice is difficult to prove in thin film samples. One argument is that there are electronic inhomogeneities on a spatial range of the order of MnSi islands within the thin film sample, i.e. a few tens of nanometers [8]. If this length scale sets an upper limit for the electronic mean free path, the latter would not be significantly larger than the diameter of a skyrmion, in which case the electrons may not at all see a skyrmion, as they might undergo scattering before traversing the skyrmion. The value of the Hooge paramater of order 10^{-1}, which is of order to what has been observed for granular metallic thin films and metal-insulator composites [19], is compatible with such an interpretation. Another aspect is that the substrate-induced strain possibly destabilizes the skyrmion phase, which may be recovered by external pressure.

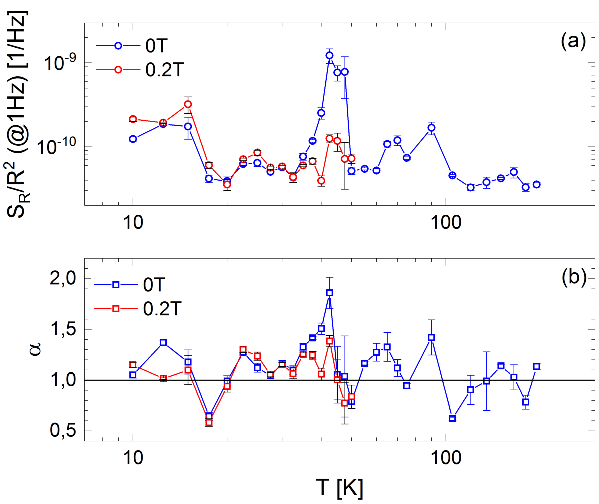

Fig. 2. (a) Normalized resistance noise PSD $S_R/R^2(f = 1\,\text{Hz})$ against temperature T for different magnetic fields $B = 0\,\text{T}$ and $B = 0.2\,\text{T}$. (b) Frequency exponent α against temperature T at for different magnetic fields, namely $B = 0\,\text{T}$ and $B = 0.2\,\text{T}$. The horizontal line marks $\alpha = 1$, see text for details.

Interestingly, however, a signature is observed upon approaching the magnetically ordered phase. Fig. 2(a) clearly shows an enhanced noise magnitude below about 50 K and above 35 K, i.e. close to T_C, of the zero field data as compared to the measurements in $B = 0.2\,\text{T}$. This is accompanied by a change of the frequency exponent α from smaller to greater than 1 for decreasing temperatures. Assuming a superposition of thermally-activated fluctuation processes causing the observed $1/f^{\alpha}$-noise one expects typical energies of $E = -k_BT \ln 2\pi f \tau_0$ for these fluctuations [20], which corresponds to $E \sim 110 - 130\,\text{meV}$ in the given temperature range using $\tau_0 = 10^{-14}\,\text{s}$ as a typical inverse phonon frequency. Furthermore, whereas the resistance noise PSD remains $1/f$-type at higher temperatures and inside the magnetic phase, Lorentzian-type spectra superimposed on the $1/f$ background have been detected in the temperature range between 50 K and 40 K, i.e. upon approaching the magnetic transition. Examples of such spectra are shown in the inset of Fig. 3 for selected temperatures $T = 44\,\text{K}$ and 47 K. Note that in Fig. 2 magnitude and frequency exponent of the '$1/f$ background' (on which a Lorentzian contribution is superimposed) is plotted. The enhanced $1/f$-noise level observed close to T_C, which may be a signature of enhanced magnetic fluctuations, becomes suppressed by a small magnetic field of 0.2 T.

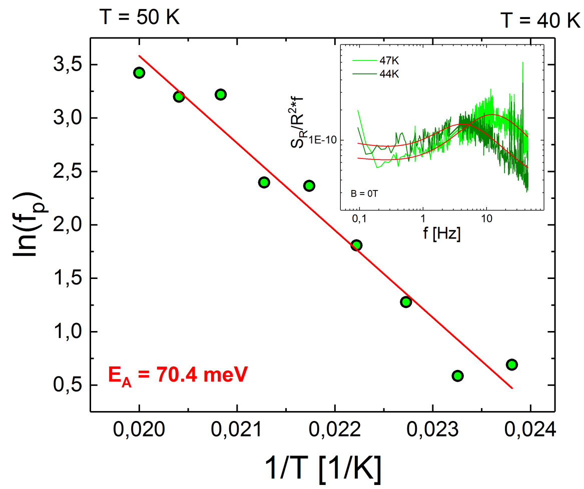

Fig. 3. Arrhenius plot of the corner frequency f_c of the Lorentzian contributions against $1/T$. A linear fit yields the activation energy $E_A = 70\,\text{meV}$ of the underlying two-level-process. Inset: Selected spectra at $T = 44\,\text{K}$ and 47 K in a plot $S_R/R^2 \times f$ vs. f with corresponding Lorentzian fits.

Very often, $1/f$-noise originates in the superposition of many two-level fluctuation processes with a certain distribution of time constants (or activation energies). In the present case, a Lorentzian spectrum with a characteristic corner frequency f_c is enhanced in our 'noise window'. The inset of Fig. 3 clearly shows for two selected temperatures that f_c shifts to higher frequencies with increasing temperatures. The main panel of Fig. 3 shows the corner frequency f_c of the observed Lorentzian spectra determined by fitting a single-two level fluctuation process superimposed on a $1/f$-like background against $1/T$ between $T = 50\,\text{K}$ and 40 K in an Arrhenius plot. The characteristic energy of this thermally-activated process can be determined from

$$f_c = f_0 \exp\left(-E_A/k_BT\right) \tag{2}$$

with k_B as the Boltzmann constant and an attempt frequency f_0. A linear fit yields a value for the activation energy of around $E_a \sim 70\,\text{meV}$. This energy may correspond to a certain region within the thin film sample that switches between the paramagnetic and magnetically ordered state. However, the corner frequency does not significantly shift with the applied magnetic field. As shown in Fig. 4 below, the process rather vanishes for larger magnetic fields. It remains almost unaffected within the magnetic phase, i.e. for fields up to $B = 0.5\,\text{T}$ and is not observed in the fully field-polarized state above 0.9 T. In the intermediate field region, the process cannot be reproduced, i.e. it occurs for certain field values.

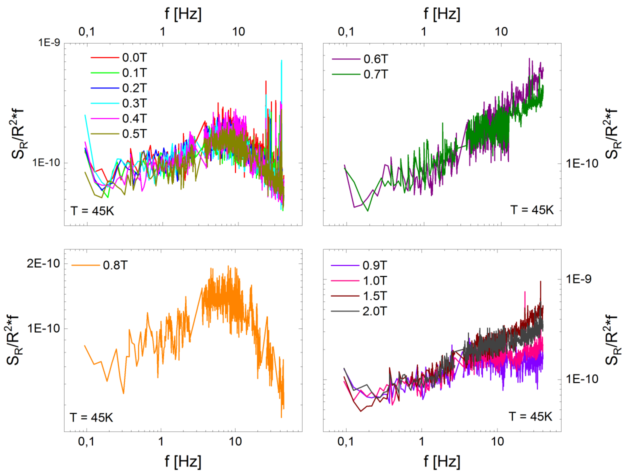

Fig. 4. Plot of $S_R/R^2 \times f$ against frequency f for different magnetic fields at $T = 45\,\mathrm{K}$, i.e. close to T_C. For applied fields up to $B = 0.5\,\mathrm{T}$, Lorentzian behaviour is observed. In the field range between $0.6\,\mathrm{T}$ and $0.8\,\mathrm{T}$ both superimposed Lorentzian and 1/f behaviour are observed. At magnetic fields exceeding $0.9\,\mathrm{T}$, the Lorentzian behaviour vanishes.

Conclusion and Outlook

In summary, we have performed first noise noise measurements on epitaxial grown MnSi thin films. In the context of skyrmion dynamics, our work was motivated by the expected effects of driven skyrmion lattices on the low-frequency fluctuation properties. In analogy to driven superconducting vortex lattices, the characteristic pinning/depinning energies, skyrmion velocities and other dynamical parameters can be accessed by analyzing broad-band and narrow-band noise. We have chosen thin-film samples which exhibit an enhanced $1/f$-noise level due the small sample volume and larger absolute impedances. We have observed generic $1/f$-type spectra, but no clear signatures of changes inside the magnetic phase. A possible reason is the existence of electronic inhomogenities, which is compatible with a Hooge parameter of order 10^{-1} and the observation of distinct two-level fluctuations. Another aspect is that, in general, the existence of a skyrmion phase in epitaxial grown thin films is less clear than in bulk single crystals, likely due to the suppression of the skyrmionic phase by substrate-induced strain. However, an enhanced $1/f$-noise magnitude and redistribution of spectral weight as well as signatures of two-level fluctuations are observed upon approaching the helical magnetic phase in zero magnetic fields.

Our results show that fluctuation spectroscopy of MnSi is feasible. Systematic investigations of the noise properties may help to better characterize the transport characteristics of thin-film samples and even to access dynamical properties of the different magnetically ordered phases. However, bulk MnSi, where the existence of a skyrmion phase can be more easily verified [21] and which do not suffer from strain effects imposed by the substrate, may be a better starting ground for accessing skyrmion dynamics. The problem of large volume/small sample impedances could be overcome by micro-structuring bulk MnSi.

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