Decomposition of 1/f noise in AlxGa1-xAs/GaAs Hall devices

著者	Muller Jens, Molnar Stephan von, Ohno Yuzo, Ohno Hideo
journal or publication title	Physical Review Letters
volume	96
number	18
page range	186601
year	2006
URL	http://hdl.handle.net/10097/53520

doi: 10.1103/PhysRevLett.96.186601

PRL **96,** 186601 (2006) PHYSICAL REVIEW LETTERS week ending 12 MAY 2006

Decomposition of $1/f$ Noise in $Al_xGa_{1-x}As/GaAs$ Hall Devices

Jens Müller* and Stephan von Molnár
Center for Materials Research and Technology (MARTECH), Florida State University, Tallahassee, Florida 32306-4351, USA

Yuzo Ohno and Hideo Ohno
Laboratory for Nanoelectronics and Spintronics, Research Institute for Electrical Communication, Tohoku University, Sendai, Japan

(Received 8 November 2005; published 8 May 2006)

We present a systematic study of the low-frequency noise in micron and submicron Hall devices made from $Al_xGa_{1-x}As/GaAs$ heterostructures. In a sample with feature size as small as 0.45 μm we observe a nonmonotonic temperature dependence of the noise power spectral densities (PSD's) at temperatures where surface states and deep-level excitations are frozen out. Near the temperature where the noise peaks, the PSD's can be described by a thermally activated two-level random telegraph signal, i.e., the $1/f$ noise originating from switching events in the highly doped $Al_xGa_{1-x}As$ layer is resolved into a single Lorentzian spectrum.

DOI: 10.1103/PhysRevLett.96.186601 PACS numbers: 85.30.−z, 73.23.−b, 74.40.+k

High-mobility two-dimensional electron systems (2DES) in III/V semiconductor heterostructures such as n-$Al_xGa_{1-x}As/GaAs$ are the subject of continuing interest in fundamental investigations, as, e.g., integer and fractional quantum Hall effect, as well as devices in electronic applications, such as high-speed modulation-doped field effect transistors, or high-sensitivity Hall magnetometers for noninvasive nanoscale magnetic measurements and biological sensing; see, e.g., Refs. [1–3] and references therein.

Studying the noise in semiconductor structures may give a further in-depth understanding of the intrinsic properties of the conductivity such as the microscopic behavior of charge carriers and their coupling to lattice defects, electronic traps, and magnetic moments. Although, since the invention of $Al_xGa_{1-x}As/GaAs$ heterostructures [4], there is a long history of noise studies of field effect transistor (FET), quantum point contact (QPC), and Hall-bar structures (see, e.g., Refs. [5–16]), no general understanding of the switching and $1/f$ noise phenomena in $Al_xGa_{1-x}As/GaAs$ devices has been reached. In these studies various mechanisms of noise have been discussed (see below). A complex interplay of these mechanisms may determine the noise behavior in relatively large samples of GaAs based materials, whereas in smaller devices the origin of a particular noise pattern may be identified. In a seminal paper by Kirtley *et al.* [5] it has been pointed out that trapping and detrapping of electrons in the n-$Al_xGa_{1-x}As$ layer, i.e., changes in the charge states of deep donor levels—the so-called *DX* centers [17]—will effect the conduction in the 2DES by a combination of electron mobility and density fluctuations. By comparison of AlGaAs/GaAs heterostructures and relatively thick AlGaAs, Hofman *et al.* have found that generation-recombination noise in the 2DES of the former, which is observed as broadened Lorentzian-type spectra superimposed on the $1/f$ background, is indeed caused by *DX*-type traps located in the remote n-doped AlGaAs layer [7]. Similar results on gated and ungated structures have been reported in Refs. [6,9–11,15]. The generation-recombination noise spectra observed in these studies were not purely Lorentzian-type as expected for a single fluctuator but rather broadened spectra or superpositions of more than one Lorentzians on top of a large $1/f$ background. The broadening has been attributed to a distribution of time constants in the space-charge region [6], the effect of inhomogeneous alloy composition on the capture and emission kinetics of the *DX* center [5], or a distribution in the barrier height [18,19].

Driven by the quest to further optimize $Al_xGa_{1-x}As/GaAs$ Hall sensors, we recently presented a systematic characterization of low-frequency fluctuations in submicron Hall devices at temperatures between 1.5 and 60 K [13] where surface states and *DX* center excitations are frozen out. In this study a surprisingly large gating effect on the $1/f$ noise was found. It was concluded that the $1/f$ noise originates from remote switching processes in the highly-doped n-$Al_xGa_{1-x}As$ layer [13] which are weakly coupled to the 2DES, e.g., by affecting the mobility of the free carriers.

The universality of $1/f$ noise in solids and the mechanisms from which it arises is of great fundamental interest [20–22]. However, as has been pointed out in Ref. [23], only limited information comes from the conventional ensemble-averaged (featureless) $1/f$-type noise power spectrum. Yet, when the averaging is incomplete and the signature of only a few or even a single fluctuator can be resolved, deviations from a $1/f$-type behavior are observed and the capture and emission kinetics of single defects can be investigated. Here we present the results of such an approach. The final goal was to investigate individual defects and the decomposition of the $1/f$ spectrum into its constituent Lorentzian components as has been demonstrated for other systems, as, e.g., Si metal-oxide-semiconductor field effect transistors [24,25] or metalinsulator-metal tunnel junctions [26]. The measurements presented in this Letter extend earlier studies of resistance fluctuations in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ FET's and QPC's, and Hall-voltage fluctuations in relatively large structures to a new parameter range. We report nonmonotonic temperature dependence and deviations from $1/f$-type behavior of the noise power spectral densities (PSD's) in a Hall device with feature size w as small as 0.45 μm. We show that the data can be described by a two-parameter random signal. For the first time in these materials we observe the decomposition of $1/f$-type spectra with the shrinking of the structure's feature sizes, i.e., the link between this universal type of noise and the individual Lorentzian spectra due to submicroscopic Hall-voltage fluctuations.

The noise data shown here are representative for devices fabricated from the present and similar $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ wafer materials. We discuss two devices in detail: a larger sample with Hall crosses of (5×5) $\mu\mathrm{m}^2$ in size and a smaller sample with feature size of (0.45×0.45) $\mu\mathrm{m}^2$. The channel length for resistance measurements is $L = 12$ μm. The $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterostructure was grown on an undoped semi-insulating GaAs (100) substrate and AlAs/GaAs superlattice buffer layer; they consist of a 1000 nm thick undoped GaAs layer, a 30 nm thick undoped $\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ spacer layer, a 60 nm thick Si-doped $\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ layer with a dopant density of 1×10^{18} cm^{-3} and a 5 nm GaAs cap layer. A 25 nm thin Cr/Au gate was deposited on top of the structures. The electron density and Hall mobility determined in measurements on the larger sample are $n = 1.5 \times 10^{11}$ cm^{-2} and $\mu_H = 2 \times 10^5$ $\mathrm{cm}^2/\mathrm{V\,s}$, respectively, at $T = 45$ K, in the dark, and zero gate voltage. Micron and submicron Hall-bar patterns were fabricated by photolithography and electron-beam lithography, respectively, followed by wet chemical etching [27]. Electrical contacts are made by alloying In/Sn. The resistivities of both samples show metallic behavior down to 5 K.

The noise power spectral density of the Hall voltage was measured using a 7-terminal ac gradiometry setup where two currents I_1 and I_2 are applied with opposite directions to two Hall crosses. The electronic circuit allows balancing both amplitude and phase of the currents, so that the Hall gradiometer output ΔV_H has zero offset. For details, see Ref. [13] and references therein. The resistance noise has been measured using a 4-terminal setup.

Figure 1(a) shows the PSD's of the larger sample with Hall cross size (5×5) $\mu\mathrm{m}^2$ at 45 K and different gate voltages. The spectrum at zero gate voltage is $1/f$-like. Also, as discussed in Ref. [13], the noise is strongly suppressed by moderate gate voltages (in this sample, at $V_g = 150$ mV the noise is suppressed almost down to the floor level). A $1/f$-type behavior is observed for all samples measured with feature sizes larger than or equal to about 0.9 μm (not shown). In contrast, the PSD's of a smaller sample (0.45×0.45) $\mu\mathrm{m}^2$ in Fig. 1(b) show deviations from $1/f$-type behavior for certain temperatures and a temperature dependence different from what is expected from the Dutta-Dimon-Horn model (DDH). According to DDH the noise level, $S(f, T) \propto (k_B T)/f D(E)$ [28], should increase linearly with temperature when the distribution of activation energies $D(E)$ is constant, i.e., for $1/f$-type behavior. In Fig. 1(b) we observe a nonmonotonic behavior: at 20 K the noise level is lowest and is still somewhat close to a $1/f$-type PSD. $S_V(f, T)$ then increases with temperature and reaches a maximum at about 45 K, where the deviations from $1/f$-type behavior are most obvious: the tail at higher frequencies is closer to $S_V \propto 1/f^2$ which is typical for a Lorentzian-type behavior. With increasing temperature the noise level then decreases again and for the curve at 60 K a tendency towards $1/f$-like behavior is recovered. Remarkably, measurements of the resistance noise on the same sample reveal a pure $1/f$-type behavior at all temperatures and gate voltages, in particular, at around 45 K where the Hall-voltage noise strongly deviates from $1/f$; see Fig. 1(c).

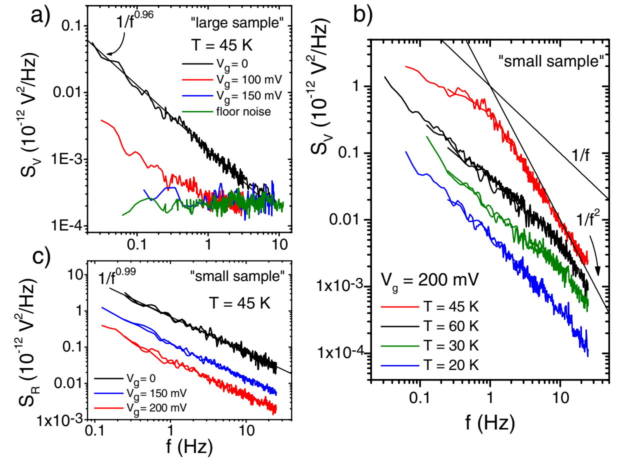

FIG. 1 (color online). Comparison of the noise power spectral densities of two samples fabricated from the same wafer (a) with a relatively large Hall-bar structure ($w \sim 5$ μm) taken at different gate voltages and fixed temperature $T = 45$ K, and (b) and (c) a smaller structure ($w \sim 0.45$ μm). In (b) the *Hall-voltage* noise is shown taken at different temperatures and fixed gate voltage $V_g = 200$ mV and in (c) the *resistance* noise at fixed temperature and different gate voltages. The applied current was $I = 2$ μA in (a), 0.4 μA in (b), and 0.5 μA in (c). Data were taken at $B = 0.5$ T. The lines in (a) and (c) are fits to $S \propto 1/f^\alpha$ yielding $\alpha = 0.96$ and 0.99, respectively. The lines in (b) indicate the slopes for $1/f$ and $1/f^2$ behavior.

The PSD's of a random telegraph signal (RTS) caused by switching between two states with voltage amplitude ΔV and lifetimes τ_1 and τ_2 is given by

$$S_V = \frac{4(\Delta V)^2}{\tau_1 + \tau_2} \frac{1}{(1/\tau_p)^2 + (2\pi f)^2} \tag{1}$$

where $1/\tau_p = 1/\tau_1 + 1/\tau_2$ [29]. Figure 2 shows the Hall-voltage PSD's taken at different temperatures in the vi-

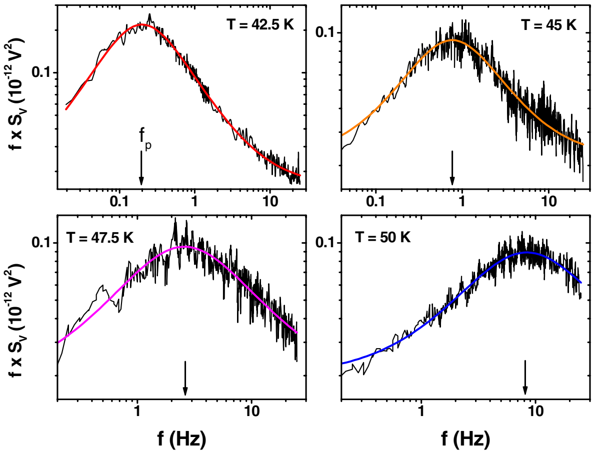

FIG. 2 (color online). PSD's of the smaller sample ($w \sim 0.45\ \mu$m) at different selected temperatures around 45 K taken at $V_g = 200$ mV, $B = 0.5$ T, and $I = 0.4\ \mu$A in a representation fS_V vs f. The lines are fits to Eq. (1) plus a small $1/f$ background term. Arrows indicate the center frequency.

cinity of 45 K in a representation fS_V vs f. This is convenient as the noise due to two-level switching appears as a peak on top of a constant $1/f$ "background." Clearly, the center frequency shifts to higher frequencies with increasing temperature which is expected for thermally activated behavior. The lines in Fig. 2 are fits to the data using Eq. (1) with amplitude and center frequency $f_p = 1/(2\pi\tau_p)$ as fitting parameters plus a small $1/f$ background term which is a constant offset. The data of all spectra taken in our frequency window are very well described by pure Lorentzians *without* considering a broadening of the spectra by some finite energy distribution.

Considering the simple case of a two-level system, i.e., a double-well model with thermally activated switching between two states, the average time τ_i spent in state i can be described by an Arrhenius law

$$\tau_i = \nu_{0,i}^{-1} \exp(E_{a,i}/k_B T) \tag{2}$$

where $E_{a,i}$ is the barrier height to escape from state i, k_B is the Boltzmann constant and $\nu_{0,i}$ an attempt frequency, typically in the order of inverse phonon frequency. The thermally activated behavior becomes apparent in an Arrhenius plot; see Fig. 3. Since only a single fluctuator is involved the activation energy can be determined with great accuracy. Indeed, the data are in excellent agreement with the simple model described by Eq. (2) yielding $E_a = 88$ meV and $\nu_0 = 6 \times 10^9$ Hz for the activation energy and the attempt frequency, respectively.

A purely Lorentzian-type RTS can be explained by an electronic switching process, i.e., trapping or detrapping events of a single electron. Such events, however, can involve surface states, deep or shallow levels (possibly forming an impurity band), and can occur in different spatial regions of the sample. Also they may couple differently to the electronic states confined in the potential well, whose noise is measured. Rather than trapping or detrapping of an electron in the space-charge region at the $Al_xGa_{1-x}As/GaAs$ interface for which significantly larger values of the activation energies are expected [6,30], we attribute the Lorentzian-type PSD at around 45 K to more shallow switching processes in the remote impurity layer, i.e., the same mechanism which leads to $1/f$ noise in the present materials. This is corroborated by the fact that the observed attempt frequency for the switching events leading to the Lorentzian-type PSD's is of the same order of 10^9 Hz as the attempt frequencies of the $1/f$ noise due to remote impurity switching [13]. Also, from Fig. 1 it is apparent that the Lorentzian-type spectrum which is most prominent at around 45 K evolves from and merges into a less Lorentzian, more $1/f$-like behavior at lower and higher temperatures. The deviations of $1/f$-type behavior which are still apparent at lower and higher temperatures may be attributed to the high- and/or low-frequency tails of other fluctuators with slightly different dynamic properties. The measured value of $E_a = 88$ meV, which has been most accurately determined from a well-defined isolated fluctuator, is somewhat larger than 12–24 meV as observed in Ref. [13]. The latter values determined from an ensemble of fluctuators, however, were measured in a sample from a different growth and at lower temperatures. The differences might indicate a distribution of activation energies in the present materials.

As has been pointed out by Kirtley *et al.* [5], τ_1 and τ_2 can be determined individually from the noise spectra if the

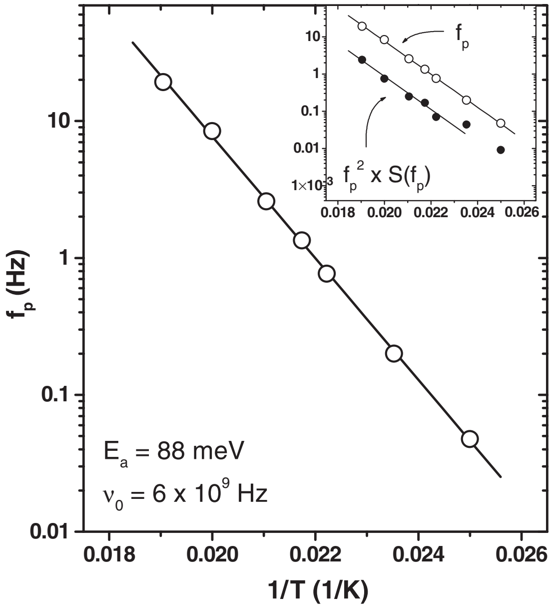

FIG. 3. Arrhenius plot of the center frequency f_p taken from fits to spectra like the ones shown in Fig. 2 vs reciprocal temperature. The line is a fit to Eq. (2). The inset also shows $f_p^2 S(f_p)$. The similar slope indicates similar activation energies for trapping and emission (see text).

two lifetimes are roughly the same. For $\tau_1 \approx \tau_2 = \tau$, both fit coefficients of Eq. (1), f_p and $f_p^2 S(f_p)$, are proportional to $1/\tau$ and the slopes in an Arrhenius plot should give a similar value for E_a, i.e., the activation energies for electron capture and emission are nearly the same. The inset of Fig. 3 shows that this is indeed observed for the present sample at $V_g = 200$ mV. This suggests that an individual trap located in the n-Al$_x$Ga$_{1-x}$As layer within k_BT of the quasi-Fermi level is the dominant source of generation-recombination noise which couples only weakly to the 2DES.

The present materials, which are widely used for high-sensitivity Hall magnetometry and thus operate in the low current regime $I = 0.1$–10 μA, show pure $1/f$-type Hall-voltage noise for structures larger than or equal to $w \sim 0.9$ μm. Submicron devices with $w \sim 0.7$ μm start to show deviations from $1/f$ for certain temperatures and gate voltages (see Ref. [13]) until for the present device with $w = 0.45$ μm the impurity configuration in the n-Al$_x$Ga$_{1-x}$As layer is such that the $1/f$ noise is resolved into a single Lorentzian. The comparison of Figs. 1(b) and 1(c) corroborates our suggestion that the decomposition of $1/f$ noise is indeed caused by shrinking of the structure's the feature size and thus lowers the degree of averaging: for the Hall gradiometry experiment with a rather small active area $A = 2w^2 = 0.405$ μm^2 the spectrum is resolved into an isolated fluctuator whereas the resistance noise with $A = Lw = 5.4$ μm^2 measured under the same conditions provides enough ensemble averaging to obscure the signature of individual fluctuators.

In conclusion, we have performed low-frequency noise studies on Hall devices made from gated Al$_x$Ga$_{1-x}$As/GaAs heterostructures of different sizes. The noise power spectral densities of larger samples with feature size in the micron range show a $1/f$-like behavior and a monotonic increase of the noise with temperature. In a sample as small as 0.45 μm we observe a nonmonotonic temperature dependence of the PSD's and deviations from $1/f$-type behavior to a thermally activated Lorentzian-type PSD. The Lorentzian is described by a two-rate kinetics and a single activation energy and attempt rate. For the latter we suggest the same origin as for the $1/f$ noise in larger devices, namely, switching events in the remote n-Al$_x$Ga$_{1-x}$As impurity layer which are weakly coupled to the 2DES. Hence, in small-area Hall devices for the first time in these materials a systematic decomposition of the $1/f$ noise in the Hall voltage to its Lorentzian constituents and thus the kinetic signature of a single fluctuator in the noise spectrum has been investigated.

We gratefully acknowledge fruitful discussions with Yongqing Li and Peng Xiong. Work is supported by NSF grant No. DMR0072395 and DARPA through ONR Grants No. N-00014-99-1-1094 and No. MDA-972-02-1-0002. The work at Tohoku University was supported partially by a Grant-in-Aid from the Ministry of Education, Japan.

[*] Electronic address: j.mueller@martech.fsu.edu

[1] Y. Li, P. Xiong, S. von Molnár, S. Wirth, Y. Ohno, and H. Ohno, Appl. Phys. Lett. **80**, 4644 (2002).
[2] K. Novoselov, S. Morozov, S. Dubonos, M. Missous, A. Volkov, D. Christian, and A. Geim, J. Appl. Phys. **93**, 10 053 (2003).
[3] G. Mihajlović, P. Xiong, S. von Molnár, K. Ohtani, H. Ohno, M. Field, and G. Sullivan, Appl. Phys. Lett. **87**, 112502 (2005).
[4] H. Störmer, R. Dingle, A. Gossard, W. Wiegmann, and M. Sturge, Solid State Commun. **29**, 705 (1979).
[5] J. Kirtley, T. Theis, P. Mooney, and S. Wright, J. Appl. Phys. **63**, 1541 (1988).
[6] S. Kugler, J. Appl. Phys. **66**, 219 (1989).
[7] F. Hofman, R. Zijlstra, and J. Defreitas, J. Appl. Phys. **67**, 2482 (1990).
[8] C. Dekker, A. J. Scholten, F. Liefrink, R. Eppenga, H. van Houten, and C. T. Foxon, Phys. Rev. Lett. **66**, 2148 (1991).
[9] S. Tehrani, A. van Rheenen, M. Hoogstra, J. Curless, and M. Peffley, IEEE Trans. Electron Devices **39**, 1070 (1992).
[10] L. Ren and M. Leys, Physica (Amsterdam) **192B**, 303 (1993).
[11] D. D. Carey, S. T. Stoddart, S. J. Bending, J. J. Harris, and C. T. Foxon, Phys. Rev. B **54**, 2813 (1996).
[12] Ç. Kurdak, C.-J. Chen, D. C. Tsui, S. Parihar, S. Lyon, and G. W. Weimann, Phys. Rev. B **56**, 9813 (1997).
[13] Y. Li, C. Ren, P. Xiong, S. von Molnár, Y. Ohno, and H. Ohno, Phys. Rev. Lett. **93**, 246602 (2004).
[14] M. Pioro-Ladrière, J. H. Davies, A. R. Long, A. S. Sachrajda, L. Gaudreau, P. Zawadzki, J. Lapointe, J. Gupta, Z. Wasilewski, and S. Studenikin, Phys. Rev. B **72**, 115331 (2005).
[15] R. Khlil, A. El Hdiy, and Y. Jin, J. Appl. Phys. **98**, 093709 (2005).
[16] V. P. Kunets, R. Pomraenke, J. Dobbert, H. Kissel, U. Müller, H. Kostial, E. Wiebicke, G. G. Tarasov, Y. I. Mazur, and W. T. Masselink, IEEE Sens. J. **5**, 883 (2005).
[17] P. Mooney, J. Appl. Phys. **67**, R1 (1990); Semicond. Sci. Technol. **6**, B1 (1991).
[18] A. van Die and J. Dijkhuis, J. Appl. Phys. **74**, 1143 (1993).
[19] F. Hooge and L. Ren, Physica (Amsterdam) **193B**, 31 (1994).
[20] P. Dutta and P. Horn, Rev. Mod. Phys. **53**, 497 (1981).
[21] M. Weissman, Rev. Mod. Phys. **60**, 537 (1988).
[22] F. Hooge, IEEE Trans. Electron Devices **41**, 1926 (1994).
[23] M. Kirton and M. Uren, Adv. Phys. **38**, 367 (1989).
[24] M. Uren, D. Day, and M. Kirton, Appl. Phys. Lett. **47**, 1195 (1985).
[25] K. S. Ralls, W. J. Skocpol, L. D. Jackel, R. E. Howard, L. A. Fetter, R. W. Epworth, and D. M. Tennant, Phys. Rev. Lett. **52**, 228 (1984).
[26] C. T. Rogers and R. A. Buhrman, Phys. Rev. Lett. **53**, 1272 (1984); **55**, 859 (1985).
[27] We find that—due to edge depletion effects—the actual feature size in our samples (here 0.45 μm) is about 0.15–0.2 μm smaller than the nominal size determined by lithography and showing in electron micrographs.
[28] P. Dutta, P. Dimon, and P. M. Horn, Phys. Rev. Lett. **43**, 646 (1979).
[29] S. Machlup, J. Appl. Phys. **25**, 341 (1954).
[30] J. Müller *et al.* (to be published).