Generation-Recombination Noise in Pseudomorphic Modulation-Doped $Al_{0.2}Ga_{0.8}As/In_{0.1}Ga_{0.9}As/GaAs$ Micro-Hall Devices

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***Abstract*—The noise spectrum in micro-Hall devices based on pseudomorphic $Al_{0.2}Ga_{0.8}As/In_{0.1}Ga_{0.9}As/GaAs$ modulation-doped heterostructures was measured between 4 Hz and 65 kHz, allowing components due to thermal, $1/f$, and generation-recombination to be characterized. Applying deep level noise spectroscopy (DLNS) in the temperature range of 77–300 K to analyze the generation-recombination part of the spectrum, two electron traps contributing to noise density were identified. An emission activation energy of 474 meV was measured for the dominant trap, corresponding to the well-known DX center originating from the AlGaAs barrier. The other deep level, with an emission activation energy of 242 meV, is probably related to defects in the InGaAs layer. The structures under investigation resulted in high-performance micro-Hall devices: a supply-current-related sensitivity up to 725 $V \cdot A^{-1} \cdot T^{-1}$ at 77 K independent of bias current, a signal-to-noise sensitivity of 155 $dB \cdot T^{-1}$ and a detection limit of 340 $pT \cdot mm \cdot Hz^{-1/2}$ at 77 K were measured.**

***Index Terms*—$1/f$ noise, deep level noise spectroscopy, generation-recombination noise, micro-Hall device.**

I. Introduction

MICRO-HALL devices fabricated on III-V heterostructures have attracted much attention because of high sensitivity, signal linearity, and low noise. Pseudomorphically strained AlGaAs/InGaAs/GaAs heterostructures [1] were optimized with respect to sensitivity and thermal stability [2], [3]. Comparatively little effort has been devoted to low-frequency (LF) noise studies for sensor application. The LF noise, however, is an important Hall device parameter, as it determines the absolute detection limit of the device. Thus, a better understanding of the origins of LF noise should contribute to further improvements in the signal-to-noise sensitivity (SNS) and, therefore, to lower detection limits, with a goal of achieving pT-range resolutions important for medical diagnostic applications.

For measurements with high spatial resolution based on small active areas of micro-Hall devices, the LF noise level becomes crucial. Higher $1/f$ noise due to a reduced total number of electrons in the device together with a much lower Hall device absolute sensitivity that scales linearly with the device width contribute to a significantly reduced SNS in smaller devices [4]. Furthermore, the higher electric fields in the device active area can cause additional generation-recombination (G-R) processes due to hot-electron trapping [5]. Accordingly, deep levels contribute to both reduced SNS and to degraded thermal stability due to changes in conductivity. Thus, a direct method for the characterization of deep levels which contribute to generation-recombination noise in micro-Hall devices is essential for proper sensor design. Investigations of deep levels in semiconductors are generally based on deep-level transient spectroscopy (DLTS). However, noise spectroscopy proves to be a quite powerful tool for probing of deep levels in the semiconductor bulk as well. Deep-level noise spectroscopy (DLNS) is a direct measurement method in case of Hall devices. In contrast to DLTS studies, no structure overgrowth or other additional device preparation is necessary. Furthermore, DLNS is quite effective in certain cases (very small capture cross sections, resonant levels, cross sections exponentially depending on temperature, etc.) where DLTS fails [6].

This paper focuses on the results of DLNS studies of centers causing LF G-R noise in pseudomorphic modulation-doped AlGaAs/InGaAs/GaAs heterostructures. Two deep levels with activation energies of about 0.47 and 0.24 eV were observed in our devices. The center with activation energy of 474 meV can be identified as the DX center in the AlGaAs; the center with activation energy of 242 meV is probably related to defects in the InGaAs active channel. The nature of these traps and their influence on micro-Hall sensor performance will be discussed.

II. Experimental Details

Using a Riber 32-P gas-source molecular-beam epitaxy system, a pseudomorphic $Al_{0.2}Ga_{0.8}As/In_{0.1}Ga_{0.9}As/GaAs$

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heterostructure was grown on semiinsulating (001)-oriented GaAs wafer. The epilayer sequence for the studied samples was the following. A 5000-Å GaAs buffer layer was grown with insertion of a ten-period 15-Å $Al_{0.2}Ga_{0.8}As/15-$ Å GaAs superlattice after 2000-Å GaAs growth in order to avoid dislocations oncoming from the GaAs substrate. This buffer layer was followed by an undoped 150-Å $In_{0.1}Ga_{0.9}As$ quantum well (two-dimensional electron gas channel), a 75-Å $Al_{0.2}Ga_{0.8}As$ undoped spacer layer, a 350-Å $Al_{0.2}Ga_{0.8}As$ heavily Si-doped supplier layer ($N_D = 2 \times 10^{18}$ cm^{-3}), and a 50-Å Si-doped GaAs cap layer ($N_D = 2.5 \times 10^{18}$ cm^{-3}). The growth temperatures were 580 °C, 465 °C, and 610 °C for the GaAs buffer, the InGaAs quantum well, and the AlGaAs barrier, respectively. The growth procedure was monitored and optimized by means of *in situ* RHEED observation and by photoluminescence (PL) [7], [8] and Raman spectroscopy [9] as postgrowth techniques.

Using standard photolithography, four-terminal Greek-cross shaped micro-Hall devices with 20-μm-square active area size were fabricated. Ohmic contacts were formed by alloying an evaporated Au:Ge:Ni metal film. Varying the temperature of the thermal annealing procedure in the range of 320 °C up to 450 °C, the contact resistance was optimized. Chemical wet-etching was used for mesa device isolation. Finally, individual chips were cut from the die, mounted and bonded on a nonmagnetic chip carrier.

Using a digital sampling oscilloscope, noise spectra measurements were performed in the 4-Hz- to 65-kHz-frequency range. The noise signal at 2^{15} points within an according time window, followed by computer-aided fast Fourier transform processing, was averaged in order to get the final noise spectrum. In order to suppress the influence of contact noise, the four-terminal technique was applied. A low-noise battery pack and a 1-MΩ series resistor were used for biasing the micro-Hall device through the bias terminals. The noise voltage signal was amplified with an ultra-low-noise preamplifier, extending the sensitivity to the nanovolt range. For temperature-dependent measurements of noise voltage fluctuations at fixed frequencies in the temperature range of 77–300 K, a model SR510 lock-in amplifier was used. In order to avoid interfering signals, the whole noise measurement setup was well shielded, and differential inputs were used.

III. Experimental Results

A. Deep-Level Noise Spectroscopy Studies

The noise voltage spectra were measured at 300 and 77 K for both possible contact alignments on the Greek-cross geometry. Representative noise spectra of a 20-μm-square size micro-Hall element measured at 77 K, and different bias currents are presented on Fig. 1; these results are essentially independent of contact alignment and bias direction.

As seen in Fig. 1, for frequencies lower than about 10 Hz, the noise spectra exhibit a plateau; this noise spectral behavior is attributed to G-R processes, and this part of the spectrum is the focus of this investigation. In the midfrequency range, $1/f$ (flicker) noise dominates and for frequencies higher than about 10 kHz; the thermal noise is all that remains. This thermal noise

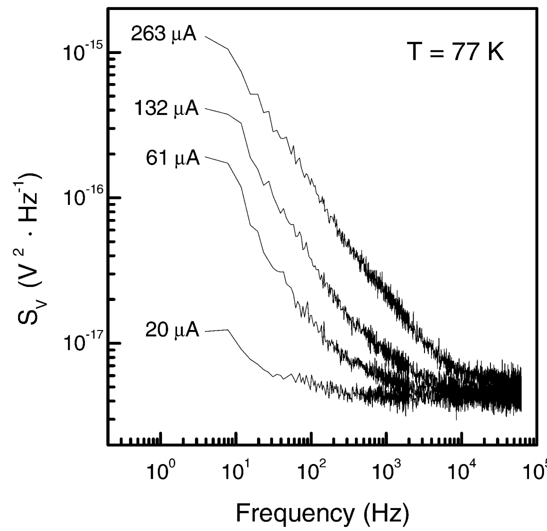

Fig. 1. Low-temperature noise voltage spectra at different bias currents. The noise signal was measured between Hall terminals.

is determined by the sample resistance and the electron temperature. As seen in Fig. 1, the thermal noise increases with elevated bias currents both because of an increase in electron temperature due to the higher electric fields and because of the increased resistance due to the nonlinearity of the velocities dependence on field strength [10].

Temperature-dependent noise measurements were used to investigate the deep centers responsible for G-R processes in the device. This method was introduced by Kirtley *et al.* [11] and later used by Carey *et al.* [12] for studies of deep metastable traps in the GaAs/AlGaAs heterostructure. The noise power spectrum $S(f_p)$ for a two-level system can be written according to [13]

$$f_p \cdot S(f_p) = \frac{1}{4\pi^2} \cdot \frac{\tau_e \tau_c}{(\tau_e + \tau_c)^2}. \qquad (1)$$

Here, τ_e and τ_c are the emission and capture times, respectively. The measurement frequency is $f_p = 1/(2\pi\tau)$, related to the time constant τ written as

$$\frac{1}{\tau} = \frac{1}{\tau_e} + \frac{1}{\tau_c}. \qquad (2)$$

The capture and emission times are taken to be exponentially dependent on temperature [12] as

$$\tau_c = \frac{\tau_{c0}}{\sqrt{T}} \cdot \exp\left(-\frac{E_c}{kT}\right) \qquad (3)$$

$$\tau_e = \frac{\tau_{e0}}{\sqrt{T}} \cdot \exp\left(-\frac{E_e}{kT}\right) \qquad (4)$$

where E_c and E_e are the capture and emission energies, respectively.

Fig. 2 shows the temperature dependence of the noise voltage fluctuations for several different frequencies. Two separate noise peaks (marked as A and B) are clearly resolved, changing their position and amplitude with varying frequency. Similar to Carey *et al.* [12], this behavior is assigned to deep traps in

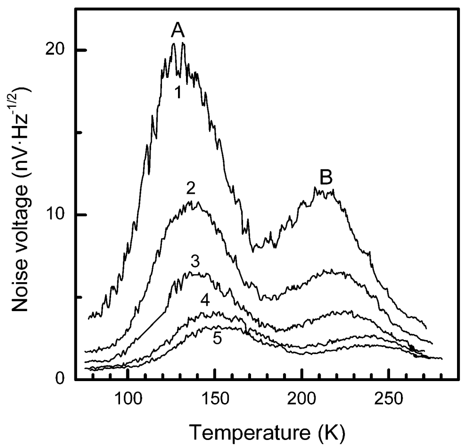

Fig. 2. Temperature dependence of the noise voltage fluctuations, measured at different frequencies of 1) 10 Hz, 2) 30 Hz, 3) 60 Hz, 4) 180 Hz, and 5) 280 Hz.

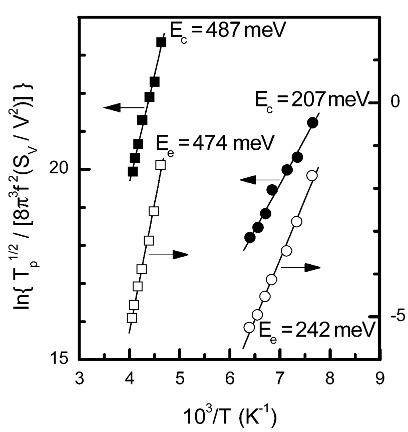

Fig. 3. Arrhenius plot used for the estimation of capture and emission activation energies.

the semiconductor materials. Measuring the peak position shift with increasing frequency, the capture and emission activation energies can be determined. In our case with $\tau_c \gg \tau_e$, these energies can be directly obtained from the slope of the Arrhenius plots $\ln(\sqrt{T_p}/2\pi f_p)$ and $\ln\left[\sqrt{T_p}/8\pi^3 f_p^2 \left(\left\langle \Delta V^2 \right\rangle / V^2 \Delta f\right)\right]$ as a function of $1/T_p$, where T_p is the temperature at which the peak occurs.

Fig. 3 contains the Arrhenius plots for both noise peaks. The emission energies E_e are determined to be 242 and 474 meV for peaks A and B, respectively. The corresponding capture energies E_c are 207 and 487 meV. The estimated experimental uncertainty for these values is $\triangle E = \pm 30$ meV. The density of the 474-meV center was also estimated using [6] to be about 1×10^{10} cm^{-2}.

From earlier DLTS studies [14], an emission energy of 440 ± 30 meV is characteristic for the DX center in AlGaAs, independent of alloy composition. This value is consistent with the emission energy measured for peak B in our devices, suggesting that the DX center is the source for one of the G-R process in our micro-Hall devices. This result is also not surprising given the presence of a relatively thick and heavily doped $Al_{0.2}Ga_{0.8}As$ barrier in the structure.

As reported earlier by Mosser *et al.* [2], the barrier thickness has to be optimized for the prevention of any parasitic parallel conduction in the barrier region, thus avoiding undesirable effects on thermal stability of micro-Hall devices. Thermal trapping effects on DX centers degrade the thermal stability of the micro-Hall device due to changes in electron concentration. Furthermore, electron trapping at DX centers in the barrier region is often a main source of generation-recombination noise and results in poor noise performance, even at lower Al composition as in our case. Accordingly, both the SNS and magnetic field detection limit deteriorate due to increased noise density. Hall experiments [15] further show that the DX level E_{DX} for Al compositions $x \leq 0.22$ are energetically localized above the band edge E_Γ and, therefore, constitute a metastable level with the capability to localize electrons [11]. With $x \simeq 0.2$ in our samples, our experimental results indicate approximately the same value for both emission and activation energies within the measurement uncertainty; these data are in a good agreement DLTS [14] and DLNS [11] results obtained for MODFET structures ($x \leq 0.22$). The condition $\tau_e \approx \tau_c$ furthermore leads to the noise signal being maximized [11]. Thus, even a metastable DX center as in our structures can be highly detrimental to the SNS and the minimal detectable magnetic field.

The Hall device absolute sensitivity S_A is proportional to both electron drift velocity v and device width W

$$S_A \equiv \frac{\mathrm{dV}_H}{\mathrm{dB}} \approx G \cdot v \cdot W \tag{5}$$

where G is the geometric correction factor. Obviously, the maximum values of absolute sensitivity occur for peak drift velocity saturation in the micro-Hall devices; in modulation-doped structures, the velocity begins to saturate for electric fields of about $2\,\mathrm{kV \cdot cm^{-1}}$. At these fields, hot-electron trapping by DX centers can dominate [5]. The increased electric field can result in additional G-R processes. In addition, since the $1/f$ noise is proportional to the electric field squared and since, as earlier pointed out, the thermal noise is increased due both to the increased resistance and the increased electron temperature, higher electric fields will also lead to increased noise across the entire frequency spectrum.

As seen in Fig. 1, the studied micro-Hall devices exhibit increased noise at higher electric fields for all measured frequencies. At frequencies around 1 kHz, a very weak shoulder appears in the noise spectra for higher bias currents. Obviously, the electric field increases with downscaling of the device size. Hence, hot-electron trapping effects chiefly degrade the small-size device characteristics. An alternative, channel-doped high-velocity micro-Hall sensors, is less sensitive to high electric fields [16], [17].

In addition to the peak B seen in Fig. 2 is a larger peak A. The level whose G-R process result in peak A has capture and emission energies of 207 and 242 meV, respectively. Earlier reports on investigations of deep traps in InGaAs layers by DLTS [18], [19] also determined activation energies comparable to our results. The G-R noise in a similar structure to that used in the present investigation, but for pseudomorphic field-effect transistors (pHEMTs), was also characterized by the DLNS technique [20]; in this study, another center with unspecified activation energy was also found in addition to the DX center and associated

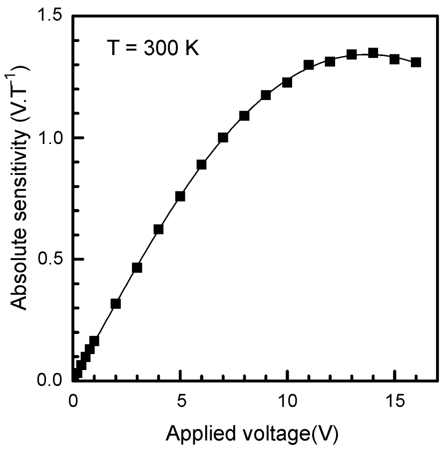

Fig. 4. Absolute sensitivity as a function of applied voltage at room temperature.

with the InGaAs channel. A conclusive interpretation of these data, however, is still somewhat unclear.

The density of this center was also estimated using [6] to be about 0.5×10^9 cm^{-2}, based on the identification of this level as being associated with the Γ valley of the InGaAs. Despite the trap density being smaller than for DX centers, the noise level is comparable, probably due to the Fermi level lying more nearly in resonance with this trap.

Photoluminescence (PL) spectroscopy and cathodoluminescence (CL) imaging at 77 K were used as accompanying characterization for our studies. Although the PL is quite intense, CL imaging in a scanning electron microscope reveals regions of less intensity; these darker regions could indicate the presence of regions of point defects.

B. Sensitivity and SNS

The absolute sensitivity as a function of applied voltage is shown in Fig. 4. As expected from (5), this relation tracks the velocity-field characteristics, saturating at an applied voltage of about 14 V corresponding to an electric field of about 2.3 kV $\cdot$ cm^{-1} for our geometry. This value is typical for the heterostructure type studied here [21].

In addition to the absolute sensitivity S_A, we also characterized the devices in terms of supply-current-related S_I and supply-voltage-related S_V sensitivities. At 300 and 77 K, supply-current-related sensitivities of $S_I = 430$ V $\cdot$ A^{-1} $\cdot$ T^{-1} and 725 V $\cdot$ A^{-1} $\cdot$ T^{-1} were determined; at both temperatures, S_I is independent of bias current.

Operating the micro-Hall device under constant voltage, one can characterize the supply-voltage-related sensitivity S_V which scales with the electron mobility. S_V was measured at 300 and 77 K for our micro-Hall devices, with maximum values of 0.165 T^{-1} and 0.45 T^{-1}, respectively. With increasing electric field in the device active area, S_V decreases due to the decreased electron mobility with increasing electric field, typical for modulation-doped heterostructures and explained in terms of hot-electron transport [22].

To characterize the SNS (i.e., the signal-to-noise ratio scaled by the magnetic field) and the detection limit, the noise spectra in the range of 4 Hz to 65 kHz were measured at different bias

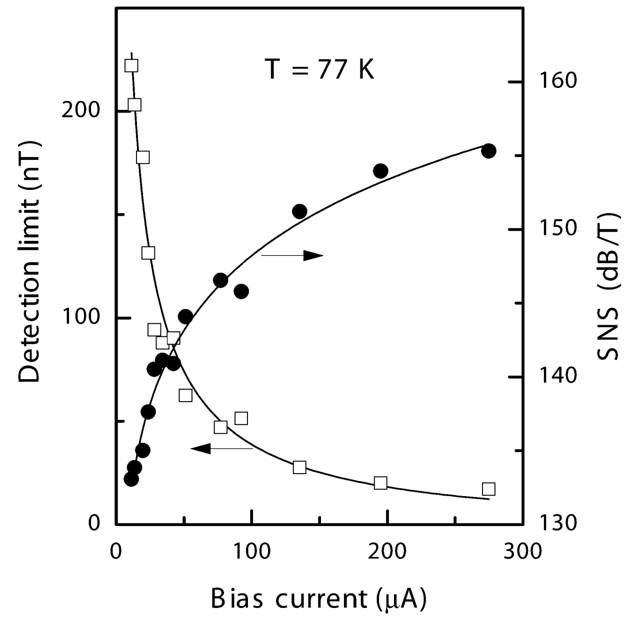

Fig. 5. SNS and detection limit as functions of bias current measured at 77 K.

currents and temperatures. The SNS and detection limit B_{DL} were determined in the upper frequency range where the noise is dominated by the Johnson (thermal) noise (at 65 kHz), according to

$$\text{SNS} \equiv \frac{S_A}{\bar{V}_{\text{noise}}} = \frac{S_A}{\sqrt{S_{V,\text{noise}}(f)\,\Delta f}} \approx vW\sqrt{\frac{en_s\mu}{4k_BT}}\sqrt{\frac{1}{\Delta f}} \quad (6)$$

$$B_{\text{DL}} = \left[\frac{S_{V,\text{noise}}(f)\Delta f}{S_A^2}\right]^{1/2} = \frac{1}{\text{SNS}} \quad (7)$$

where e is the electron elementary charge, n_s the two-dimensional electron concentration, μ the electron mobility, T the temperature, k the Boltzmann constant, V_{noise} the noise voltage fluctuation measured in equivalent noise bandwidth Δf, and $S_{V,noise}$ the voltage noise spectral density.

The results for both quantities at 77 K are shown in Fig. 5. At a bias current of $I = 275$ μA, the SNS reaches the maximum value of about 155 dB $\cdot$ T^{-1}, corresponding to a detection limit of 17 nT. A similar behavior was observed at 300 K revealing a maximum SNS of about 141 dB $\cdot$ T^{-1} and a detection limit of about 80 nT at a bias current of $I = 325$ μA. Using the figure of merit, the detection limit scaled by the width W of the device active region, the detection limit of 340 pT $\cdot$ mm $\cdot$ Hz$^{-1/2}$ and 1.6 nT$\cdot$mm$\cdot$Hz$^{-1/2}$ at 77 and 300 K, respectively, are measured.

IV. Conclusion

The low-frequency noise of micro-Hall devices based on pseudomorphic modulation-doped $Al_{0.2}Ga_{0.8}As/In_{0.1}Ga_{0.9}As/GaAs$ heterostructure has been characterized using deep-level noise spectroscopy. Two deep levels contributing to low-frequency noise are detected.

One trap with an emission energy of 474 meV and a capture energy of 487 meV is assigned to the well-known DX center originating from the AlGaAs barrier region. The DX center is shown to contribute significantly to the noise density even for an Al composition of 20%. The other deep level exhibits emission and capture energies of 242 and 207 meV, respectively. This level appears to be associated with centers in the InGaAs channel. The micro-Hall devices fabricated with 20-μm-square size exhibit at 77 and 300 K a high supply-current-related sensitivity of $S_I = 725\ \mathrm{V \cdot A^{-1} \cdot T^{-1}}$ and $S_I = 430\ \mathrm{V \cdot A^{-1} \cdot T^{-1}}$; the SNSs are 155 dB $\cdot\ \mathrm{T^{-1}}$ and 141 dB $\cdot\ \mathrm{T^{-1}}$ at 77 and 300 K, respectively. These sensitivities result in detection limits scaled by the width of the active device region of 340 $\mathrm{pT \cdot mm \cdot Hz^{-1/2}}$ and 1.6 nT $\cdot$ mm $\cdot\ \mathrm{Hz^{-1/2}}$ at 77 and 300 K, respectively.

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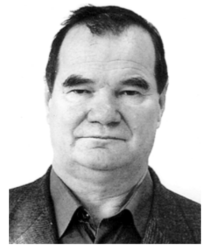

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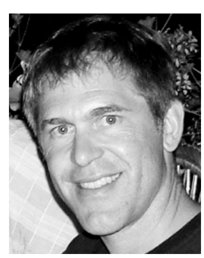

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