Correlation between flicker noise and current linearity in ferromagnetic-GaAs-metal tunnel contacts.

K. Fobelets, S. Rumyantsev, W. Van Roy, R. Vanheertum, and M.S. Shur

Abstract – The low frequency noise behavior of the in-plane current through ferromagnetic tunnel contacts on a III-V semiconductor is evaluated. Measurements are performed between ferromagnetic and ohmic contacts and between the two ferromagnetic contacts which have different coercive fields in a lateral [Ta/IrMn/CoFe]/AlO_x/GaAs/AlO_x/[CoFe/NiFe/Ta] structure. The resistance and current noise spectral density of the CoFe/NiFe/Ta contact are higher than that of Ta/IrMn/CoFe. Strong generation-recombination noise is found in high resistivity devices. It is assumed that the deep level traps are due to DX centers in the AlGaAs layer, possibly resulting from the diffusion of Ni into the semiconductor.

I. INTRODUCTION

Transport of spin polarized electrons through a semiconductor is of great interest to the semiconductor industry searching for additional mechanisms of controlling the current. In these structures, two ferromagnetic stripes (FM) are used to contact a two-dimensional electron gas. One contact is used as spin injector, the other as spin detector [1]. In order to obtain successful spin injection/detection in a semiconductor, the spin impedance mismatch caused by the contacts must be minimized [2]. The introduction of tunnel barriers between the contact and the semiconductor introduces a spin dependent resistance on a diffusive semiconductor [3]. Such a structure can be compared to the tunneling magneto-resistance structures that use a thin oxide barrier between the ferromagnetic contacts. Oxide based tunnel injectors have shown relatively good spin injection characteristics at higher temperatures (>80K). These tunnel injectors are based on CoFe/AlO_x/(Al)GaAs or CoFe/MgO/(Al)GaAs contacts, where the thickness of the sandwiched oxide layer and the doping profile of the (Al)GaAs surface layer have to be optimized for spin injection performance. The CoFe is normally combined with an antiferromagnet such as IrMn and NiFe to form a multilayer contact structure with a well controlled magnetization curve. The use of CoFe, IrMn, NiFe and AlO_x or MgO in III-V technology is quite uncommon, and processing techniques need to be adapted to these materials. Therefore, the quality and thickness of the ferromagnetic/oxide sandwich is not guaranteed and the impact of metal diffusion on the semiconductor material is not yet clear. One possible technique to investigate the quality of the FM/oxide/semiconductor contact is low frequency noise measurements. Low frequency noise in the measurement yield information about the correlation between material quality and device operation. In particular, low frequency noise characteristics can help identify the electrically active defects within the material, especially those related to generation-recombination noise [4]. The measurement of generation-recombination noise allows the extraction of the activation energy, concentration, and capture cross section of the traps responsible for the noise. This in turn gives an insight into the heterogeneities and defects introduced by the growth and fabrication processes.

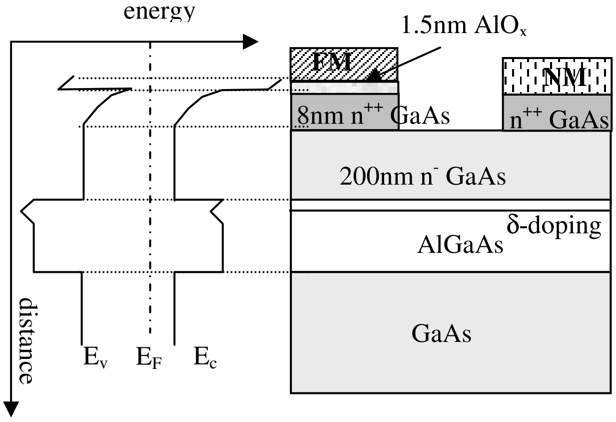

Fig. 1: Left: schematic energy band diagram, right: layer structure and ½ of the contact arrangement. FM=ferromagnetic contact, NM = normal ohmic contact.

In this paper, we investigate the behavior of a [Ta/IrMn/CoFe]/AlO_x-GaAs-ohmic, a ohmic-GaAs-AlO_x/[CoFe/NiFe/Ta] and [Ta/IrMn/CoFe]/AlO_x-GaAs-AlO_x/[CoFe/NiFe/Ta] contact configurations via low frequency noise measurements. We find a correlation between the current drive of the tunnel contact and the magnitude of the noise spectral density. Surprisingly, we find a higher resistance for the CoFe/NiFe/Ta contact and a strong indication of deep level traps. These two parameters might be linked to Ni diffusion into the GaAs/AlGaAs causing an increase of the number of DX centers in the heterojunction.

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II. DEVICES AND MEASUREMENT SET-UP

Fig. 1 shows the layer structure and schematic energy band diagram of the devices under study. The layer structure is similar to an I-HEMT [5]. The unipolar devices have a lateral configuration with four surface contacts in an ohmic-FM1-FM2-ohmic arrangement. The width of the device is 2 μm whilst the FM contact length is between 100 and 800 nm. The spacing between the FM contacts is 200 or 400 nm. The spacing between FM and ohmic contact is 20 μm. The GaAs channel is modulation doped via a δ doping in the underlying AlGaAs layer. This results in electron mobilities in the channel of approximately 5000 cm^2/Vs and a high channel conductivity of the order of 10^{-4} S. The resistance of the ohmic contacts is of the order of 10 Ω. The current-voltage characteristics were measured using an HP 4155B semiconductor parameter analyzer. The low-frequency noise was measured using a shielded probe station with 10-μm diameter tungsten probes under controlled pressure, in a frequency range from 1 Hz to 100 kHz at 300 K. The voltage fluctuations S_V were analyzed using a computer controlled SR770 FFT Spectrum Analyzer. Background noise was measured using probed unbiased devices and was subtracted from biased measurements before further data processing. The spectral noise density of the short circuit current fluctuations, S_I, was calculated using the expression:

$$S_I = S_V\left[(R_L + R_d)/(R_L R_d)\right]^2, \qquad (1)$$

where R_d is the device differential resistance and R_L is the load resistance. Measurements were carried out on multiple devices with different contact areas. No correlation between normalized noise density level and contact area was found, nor between the occurrence of deep traps and contact area.

III. MEASUREMENTS

A. Current-voltage characteristics

Fig.2 shows typical current voltage characteristics between the different contacts. The current drive between the Ta/IrMn/CoFe – ohmic contacts is higher than that between the Ta/NiFe/CoFe – ohmic contacts. This is true for all devices measured. In particular, the resistance of the contacts was within the range 10^3-10^6Ω and 10^6-10^8Ω for Ta/IrMn/CoFe and Ta/NiFe/CoFe, respectively. As a result, the current voltage characteristic measured between two FM contacts is completely determined by the Ta/NiFe/CoFe contact and it coincides with the Ta/NiFe/CoFe – ohmic characteristic. The reason for this surprising difference – as the resistance of NiFe is lower than IrMn – might be due to different diffusion behavior of Mn and Ni into the semiconductor. Both metals diffuse readily into GaAs at low temperatures. As the NiFe containing FM contact is deposited before the IrMn one, the thermal load on the NiFe contact is higher and thus Ni has potentially diffused further into the GaAs than Mn. Moreover, at the low temperatures used, it is expected that Mn diffusion into GaAs creates good magnetic contacts [6], whilst the diffusion of Ni increases the density of deep level traps in the material [7].

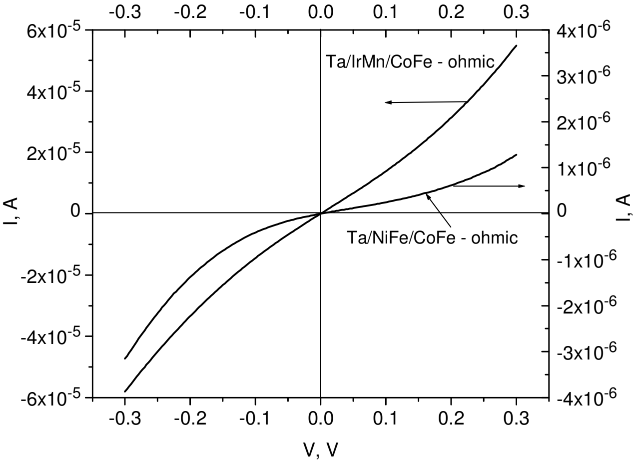

Fig. 2: Current-voltage characteristics measured between the ohmic and FM contacts. The FM-FM characteristic is the same as the dashed one.

Although the general shape of the current-voltage charactristics is the same for all devices, the current level differs by a factor 10^3 for low and high resistance devices which have the same device and contact geometry. A clear difference in noise behavior is found for these two types of devices.

B. Noise measurements

Fig. 3 gives the normalized low frequency current noise density S_I/I^2 between the different contacts and for different bias voltages: ±0.3V, for a low resistance device.

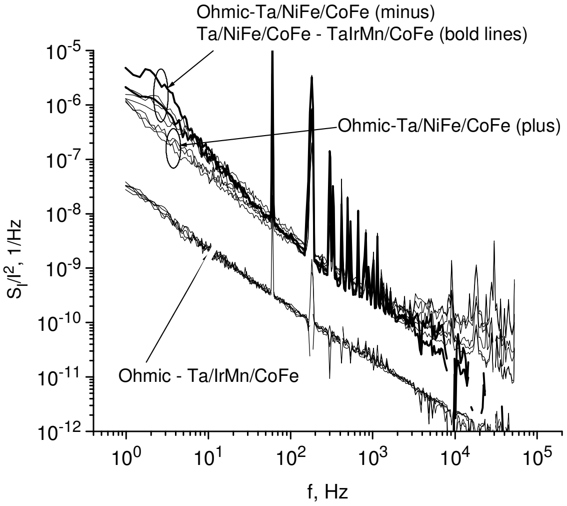

Fig. 3: Normalized low frequency noise density for the low resistance device measured between the different contacts and for different bias voltages.

The low frequency noise characteristics show a 1/f-like dependency for all contacts. We see that the noise from the Ta/IrMn/CoFe contact is smaller than that from the Ta/NiFe/CoFe contact. For the IrMn FM, the normalized noise is independent of the bias, as expected for a structure with an ohmic behavior. However, for the NiFe FM the noise is bias and polarity dependent. The noise in the FM-FM measurements is determined by the contact with the highest resistance (NiFe). The polarity dependence could be due to the magnetic character of the contacts. Application of low noise magnetic fields might shed more light on this issue. However, the noise characteristics of the NiFe contacts were not reproducing well. There was a long memory effect of the applied voltage. This implies that applying a current changes the charge state of some trap levels in the oxide. Once the charge in the trap is changed, it requires minutes or even hours for the relaxation to happen indicating the role played by deep level traps with very long relaxation times. In general, we found that the higher the contact resistance, the higher is the noise level. The occurrence of deep level traps seems to be related to the use of NiFe in the FM contact as this behavior was not seen for the Mn containing FM contacts in the low resistivity devices.

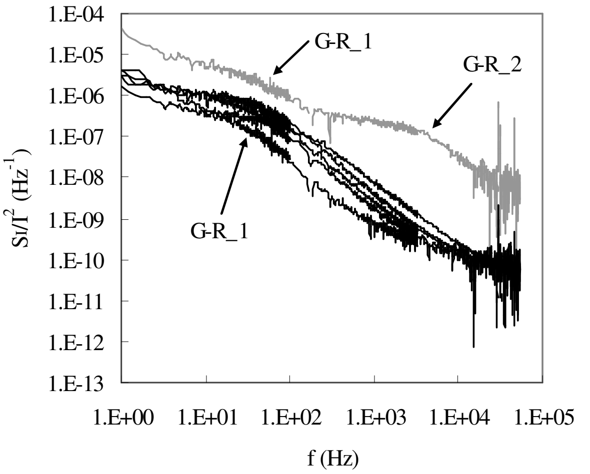

Fig. 4: Current noise spectral density normalized to the square of the current as a function of frequency for different bias voltages between 0 and 0.3V for the Ta/IrMn/CoFe-ohmic contact in a high resistivity device. Black: the same device geometry as in fig. 3 and grey: smaller contact area.

The increased resistivity and the larger noise of the Ta/NiFe/CoFe contact can be attributed to an increased number of deep level traps. In [7] it was argued that Ni diffuses readily in the semiconductor at low temperatures and causes an increase in deep level traps. If this reasoning is correct then we should also see the occurrence of deep level traps in the high resistance devices in the low frequency noise measurements. Indeed, we found that many high resistive devices exhibit generation-recombination noise.

Fig. 4 gives the normalized low frequency current noise characteristics for two high resistive devices. The contact area is the same as the device of fig. 3 for the black characteristics and is smaller for the grey characteristic. The measurements presented are those between the Ta/IrMn/CoFe and ohmic contact. The Lorentzian shape of S_I/I^2 indicates the occurrence of generation-recombination noise [4]. This means that specific traps in the structure play an important role in the conduction process. The corner frequency, f_c of the Lorentzians is found by plotting $S_I \ x \ f$ as a function of frequency, giving f_c at ~40 Hz (GR_1) and at ~4 kHz (GR_2). The low frequencies indicate deep level traps. The GR_1 trap is only found in high resistivity devices, whilst the GR-2 trap is sometimes vaguely present in the low resistivity devices too. The amplitude of the Lorentzian plateau is related to the trap concentration [8], indicating a large trap density for the high resistivity devices. The deep level traps seen here are very similar to the DX center traps typically found in AlGaAs/GaAs HEMTs [9]. Our material system is identical to the HEMT and therefore we assume that the GR noise seen in our devices is related to a high density of DX levels in the AlGaAs layer. Stronger proof for this conjecture can be obtained by studying the GR frequency shift as a function of temperature. As the homogeneity of the GaAs/AlGaAs MBE growth is excellent, the variation in trap density is associated with fabrication issues. Due to the difference in noise character of the high and low resistivity devices and the poorly behaving NiFe FM contacts, we associate the increased density of DX centers in the high resistivity devices to Ni diffusion into the semiconductor. This assumption is strengthened by the observations in [7] that show that Ni diffusion into GaAs/AlGaAs increases the density of DX centers

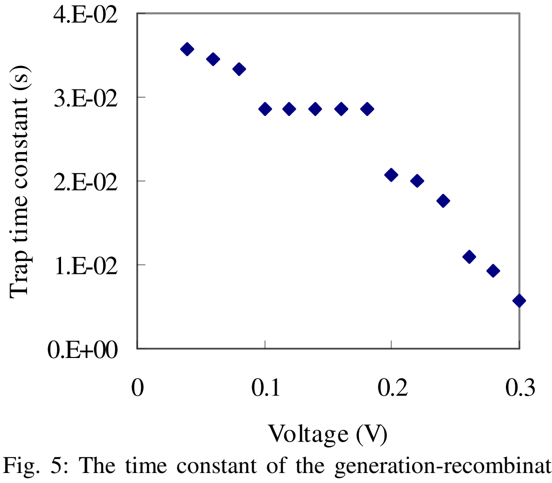

Fig. 5: The time constant of the generation-recombination noise (GR_1) as a function of the bias voltage for the high resistivity device.

f_c determines the time constant of the trap involved in the generation-recombination process: $\tau=1/2\pi f_c$ [4]. τ is given for GR_1 as a function of the applied voltage in fig. 5. The time constant of the deep level trap is of the order of tens of ms and shows a decrease with increasing bias. τ of GR_2 is tenths of ms and shows a similar dependence on the voltage.

Whilst in the low resistivity devices $S_I \propto I^2$ for the IrMn contact, this is not the case for the high resistivity devices. This deviation can be clearly seen in fig. 6 that shows the normalized current spectral noise density as a function of current. Non-monotonic dependence of noise versus current is observed in these devices at low frequencies.

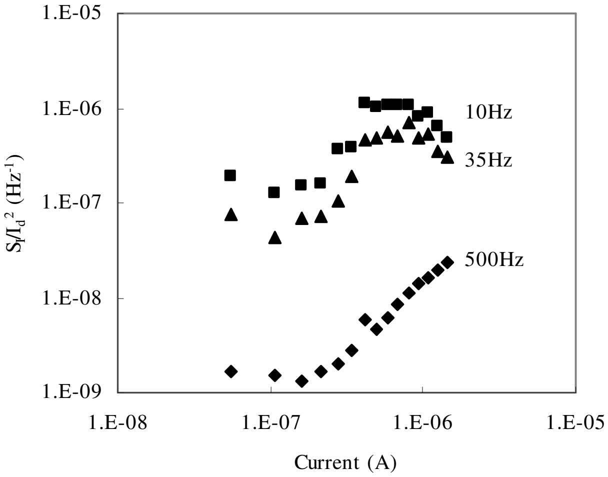

Fig. 6: Normalized noise current spectral density as a function of current at three different frequencies for the device of fig.5.

This type of non-monotonicity was also observed in GaN/AlGaN LEDs and was associated with generation-recombination noise and thus with specific traps in the semiconductor [10]. This strengthens the assumption that the GR noise in our devices is indeed associated to DX centers in the GaAs/AlGaAs heterojunction.

III. CONCLUSION

Low frequency noise measurements demonstrate that Ni containing ferromagnetic contacts have a higher resistivity and a higher noise level than Mn containing contacts. In the worst cases, strong generation-recombination noise occurs that is consistent with deep level traps similar to those associated to DX centers in GaAs/AlGaAs HEMTs. We postulate that the Ni containing contacts cause a degradation of the GaAs/AlGaAs channel in our devices resulting in higher device resistivities and the occurrence of strong deep level traps with long relaxation times. The increase of the density of DX centers in AlGaAs can be due to Ni diffusion during the low temperature fabrication stages. Further characterization, using low temperature noise measurements to establish the shift in the corner frequency of the GR noise, is necessary to proof this conjecture.

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