Low frequency noise of GaSb layers on GaAs substrate

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***Abstract*— The low frequency noise of GaSb layer was studied with four-point probe method. Such measurements supported by numerical calculations allow for the identification of the non-resistance low frequency noise introduced by metal/interface (contact), as well as the resistance noise from near-contact area and the noise related to the entire layer can be evaluated. The low frequency noise related to contacts for Te-doped GaSb sample is significantly larger than for Be-doped samples with the comparable doping level. No low frequency noise from contacts and the layer was detected for highly Be-doped GaSb.**

Keywords*— *GaSb, low frequency noise, contact noise, four-point probe method

I. INTRODUCTION

Among the III-V compounds, gallium antimonide (GaSb) is one of the most important for optoelectronic devices. It can be used as the basic component, e.g., in InAs/GaSb superlattice or as the substrate. There are many various ternary and quaternary III-V compounds as well as superlattices lattice-matched to GaSb, which makes it an attractive substrate for growing both infrared (IR) emitters and detectors. However, growing IR detector on GaAs substrate instead of on GaSb has a few advantages [1] [2], e.g., better thermal conductivity, lower cost, and much lower absorption coefficient in infrared spectral range, which makes the conversion into immersion lens, and so increase the detectivity, possible. On the other hand, lattice mismatch exists between epitaxial GaSb layer and GaAs substrate, so the growing technique should be optimized to balance the strain and reduce density of dislocations [3]. It is possible provided the necessary feedback is obtained on the quality of the grown GaSb-on-GaAs layer. Among many available methods, measurement of the low-frequency (lf) noise is very interesting as it is extremely sensitive to the quality of both materials and devices [4]. Nevertheless, this is non-trivial technique, as a result the lf noise parameters were not included in Dutta et al. [5] comprehensive review covering physics and technology of gallium antimonide. The main difficulty in application of the lf noise technique in characterizing properties of GaSb layer is the extraction of the lf noise originating from this layer from the total measured noise. This is a challenge due to the high contact-related noise contribution, which can be much higher than the lf noise of the layer. It is not so unexpected because contact metal-semiconductor interface contains various defects, e.g., voids, grains, and oxides, which are non-uniformly distributed [6].

This paper explores the idea of using low frequency noise as a tool for evaluation of various GaSb layers deposited on GaAs substrate. It is demonstrated that the contact/layer related noises can be evaluated, to some extent, with measurements and numerical calculations for the four point-probe samples.

II. EXPERIMENT

A. Samples

The GaSb layers were grown on the semi-insulating GaAs substrates using the interfacial misfit array growth method. The growth temperature was identical for all examined the layers. The thickness of GaSb layers was in the range of 1-1.3 μm. The samples differed both in doping type and concentration: D581, D585, and D631 are p-doped with beryllium (Be), while D580, D584 are n-doped with tellurium (Te). For electrical measurements the square-shape samples with four 1 mm in diameter $In_{95\%}$-$Zn_{5\%}$contacts located near the corners were prepared. The following procedure used. A 5×5 mm samples were degreased in 2-propanol and then placed in an oven with laminar N_2 or N_2+HCl flow. $In_{95\%}$-$Zn_{5\%}$ fragments were etched in 1:1 HCl:H_2O solution for 60 s before being placed at the corners of the samples. Next, the annealing in N_2+HCl flow was started. After the temperature reached contact melting point hydrochloric acid vapor flow was turned off. Subsequently, the samples were further annealed in 300°C for 10 minutes. After that, the heater was turned off and the samples were allowed to cool. In general, this procedure forms ohmic contacts, which allow for Hall measurements. In Table I the carrier concentrations in GaSb layers obtained from this measurement are provided.

TABLE I. MEASURED CARRIER CONCENTRATION OF GASB LAYERS.

Label	Carrier Concentration at 300 K [cm^{-3}]
D581, D585, D631, D580, D584	1×10^{17} (p), 7×10^{17} (p), 5×10^{18} (p), 2×10^{16} (n), 7×10^{17} (n)

B. Four-point probe method

The low frequency noise of devices under test (DUT) was measured with four-point probe method. The setup for this measurement is presented in Fig. 1. The bias current was provided to the DUT current terminals (CT) from the quasi-current source formed by external dc voltage U_s and the large-value resistance R_B (R_B was about fifty times greater than DUT resistance R_{DUT}). Power supply noise was suppressed by the filter sections. The resistance R_{DUT} was known, because the voltage across the DUT, U_{DUT}, and bias current I were continuously monitored. The voltage noise signal was acquired from the voltage terminals (VT) V1-V2 and amplified by two differential amplifiers, W1, W2. The cross-correlation technique [7] was then used to eliminate the (uncorrelated) equivalent input voltage noise of the amplifiers. In practice, the 30 dB lower signal could be detected (in acceptable averaging time) in comparison to the measurements with only one amplifier.

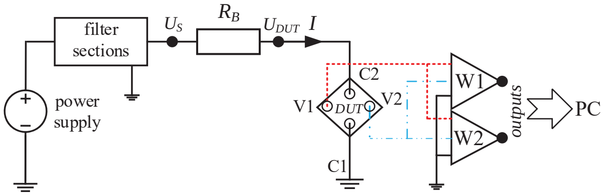

Fig. 1. The setup for voltage noise cross-correlation measurements with four-point probe configuration.

In Fig. 2, the examples of power spectral density (psd) S_{VT} measured at different temperatures for sample D580 are shown. The observed low frequency noise includes both the $1/f$ and generation-recombination (g-r) noise.

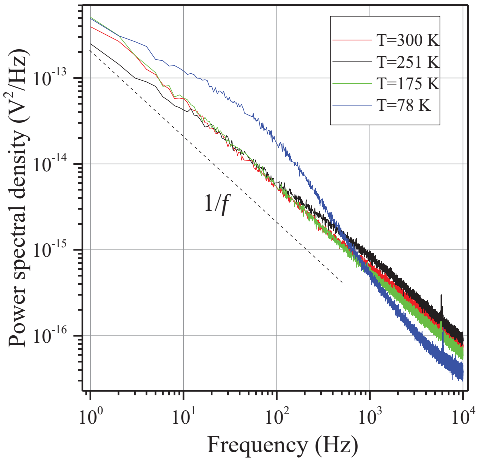

Fig. 2. The measured power spectral densities of voltage fluctuations for sample D580 biased with constant current I = 160 μA at several temperatures.

The four contacts of the DUT provide the possibility to measure lf noise in several configurations. For the arbitrarily placed current and the voltage terminals the spatially uncorrelated resistivity fluctuations produce fluctuations (resistance noise) at voltage terminals with psd given [8]

$$S_{VT} = \frac{\sum_{\alpha}\left(i_{\alpha} j_{\alpha}\right)^{2} S_{r,\alpha}}{I^{2}} \qquad (1)$$

In this equation, the lumped network model of DUT was adopted after ref. [8]. Namely, i_α and j_α are the currents in α-branch of the original or adjoint networks, and $S_{r,\alpha}$ is the psd of the resistance fluctuations in this branch (local noise). The adjoint network is identical to the original network except for the current I being provided through VT and the voltage noise being measured at CT. It stems from Eq. (1) that S_V is proportional to the bias current squared I^2. The bias independent quantity can be defined as:

$$\frac{S_{VT}}{I^{2}} \equiv S_{R} = \frac{\sum_{\alpha}\left(i_{\alpha} j_{\alpha}\right)^{2} S_{r,\alpha}}{I^{4}}. \qquad (2)$$

The coefficient $(i_\alpha j_\alpha)^2/I^4$ in equation (2) can be interpreted as the amplification factor of the local noise $S_{r,\alpha}$.

Equation (2) was used to calculate the noise amplification factor for the geometry of examined samples with four finite size contacts near the sample corners. In the numerical calculations the DUT was modeled as two dimensional homogenous ($r_\alpha = r$) structure and node-voltage method was used to find local currents i_α, j_α. In Fig. 3, the distribution of the coefficient $(i_\alpha j_\alpha)^2/I^4$ is shown for two different arrangements of the current and voltage terminals. In the first case (Fig. 3a), the current is provided diagonally to terminals AD, and the noise is measured at the same terminals. Such configuration is denoted as $\mathrm{AD_{CTVT}}$. As can be seen, in this case the noise amplification factor is significantly non-uniform and high in the near-contact areas. Consequently, the noise measured in this configuration is related almost exclusively to these areas. In the second case, the current is provided in the same way (AD terminals) but the voltage noise is measured at different pair (BC) – configuration $\mathrm{AD_{CT}BC_{VT}}$. Results for this case are presented in Fig.3b. The noise amplification factor is distributed more regularly. Consequently, the noise measured in this configuration is related to almost the entire sample, however, contributions from near-contact areas are still substantial.

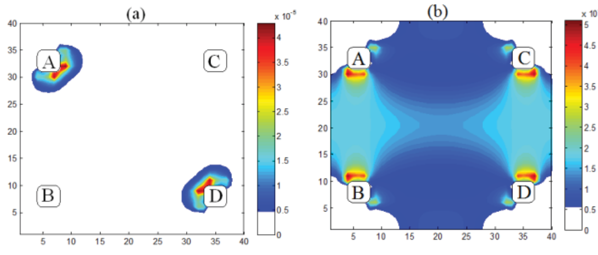

Fig. 3. The calculated value of noise amplification $(i_\alpha j_\alpha)^2/I^4$ for DUT geometry and contacts in two cases: the first (a), when AD is current and simultaneously voltage terminals ($\mathrm{AD_{CTVT}}$), and the second (b) when AD is current terminal, but BC is voltage terminal ($\mathrm{AD_{CT}BC_{VT}}$) White color is assigned for values, which satisfy the condition $(i_\alpha j_\alpha)^2/I^4 < 0.1\max[(i_\alpha j_\alpha)^2/I^4]$. The dimensions are in arbitrary units.

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For resistance noise, i.e., the noise originated from resistance fluctuations, the reciprocity principle forces that power spectral densities measured in two reciprocal configurations, e.g., $AD_{CT}BC_{VT}$ and $BC_{CT}AD_{VT}$ should be equal. The principle is valid even when the sample is non-homogenous, and contains local noise sources with different physical origin [9]. Breaking of this rule indicates that the measurement results are related to non-resistance noise of the contacts rather than to resistance noise of the semiconductor layer. The former can be explained e.g., by the depleted region of metal/semiconductor interface.

When the principle rule is obeyed the four-point probe allows for further evaluation of the noise sources homogeneity. For homogeneous distribution, i.e., for $S_{r,\alpha} = S_r$, the frequency dependence of psds $S_R(f)$ measured in different configurations should remain unchanged, and their magnitudes should remain in a constant relation. For example for configurations AD_{CTVT} ($S_{R\text{-AD}}$), BC_{CTVT} ($S_{R\text{-BC}}$) and $AD_{CT}BC_{VT}$ ($S_{R\text{-AD\_BC}}$) the calculated ratio of psd magnitudes is $S_{R\text{-AD}}/S_{R\text{-AD\_BC}} = S_{R\text{-BC}}/S_{R\text{-AD\_BC}}$ ($\cong 2.9$). In other words, the noise measured on current contacts in reciprocal configurations should be equal. Any deviation from this relation means that the distribution of noise sources in the sample is inhomogeneous. In particular, larger values of this ratio indicate that noise sources located near the contacts are more prominent.

III. RESULTS

Samples were tested for obeying the reciprocity rule by the measurements in complementary $AD_{CT}BC_{VT}/BC_{CT}AD_{VT}$ configurations. Apart from these, noise was also measured on certain current contacts i.e. in XY_{CTVT} configuration (XY = AD, AB, AC, BC, ...). Out of five DUTs only for samples D584, D585 reciprocity rule held. For sample D584 the ratio $S_{R\text{-AD}}/S_{R\text{-AD\_BC}} \cong S_{R\text{-BC}}/S_{R\text{-AD\_BC}}$ $S_{R\text{-}C}/S_{R\text{-}L} \cong 1$, whereas for sample D585 $S_{R\text{-AD}}/S_{R\text{-AD\_BC}} \cong 3.5$ and $S_{R\text{-BC}}/S_{R\text{-AD\_BC}} \cong 10$. These results are consistent with the concept that the distribution of local noise sources in these samples is inhomogeneous. In particular, in sample D585 the noise of near-contact regions.

DUTs D580, D581 did not obey the reciprocity rule and moreover noise measured in XY_{CTVT} configurations (i.e. on current contacts) depended significantly on the terminals (XY) selected for measurements. Thus, non-resistance noise of the contacts dominates in these samples.

A. *Contact-related low frequency noise*

Regardless of its origin (resistance/non-resistance), the contact-related lf noise can be measured in XY_{CTVT} configuration. In such configuration the noise can be related to the sample resistance and *relative contact noise* can be defined as: $C_{lf} = S_{VT}/V^2 = S_R/R^2$. In Fig. 4, the coefficient C_{lf} determined at 300 K for different samples and CT-configurations is shown as a function of free carrier concentration (doping) in GaSb layer. The highest p-doped layer D631 did not exhibit lf noise: the value 7×10^{-19} Hz^{-1} attributed to this sample in Fig. 4 is the amplifier noise limit. For other devices, the values of C_{lf} are scattered depending on the terminals used during the measurements. Nevertheless, a rough dependence on carrier concentration can be observed: relative noise decreases as carrier density increases.

Another observation that can be derived from Fig.4 is that for a similar carrier concentration the p-type layer (sample D585) exhibits about two orders of magnitude lower contact noise than n-type layer (sample D584). As shown in Fig. 5, in which the temperature dependence of the coefficient C_{lf} is presented, this relation holds in a wide range of temperatures. The curves for beryllium p-doped and tellurium n-doped samples exhibit different behaviors: for p-type layers (D585, D581) the contact noise weakly depends on the temperature as opposed to n-type layers (D584, D580), for which C_{lf} changes by ~2 orders of magnitude with a complex temperature dependence.

The magnitude of the coefficient C_{lf} found in this study can be compared with the only other results found in the literature. Rolland et. al. [10] studied lf noise of Te-Au contact to n-type GaSb and Au or AuZn contacts to p-type GaSb. Both GaSb layers were highly doped to $N \approx 10^{18}$ cm^{-3}. The general conclusions that can be drawn from theirs measurements are consistent with ours: both Au or AuZn-alloy contacts to p-doped GaSb exhibit no lf noise after annealing in pure hydrogen atmosphere. The Te-Au contact to n-type GaSb exhibits 1/f noise with the magnitude $C_{lf} = 3{,}3\times10^{-17}$ Hz^{-1} much lower than our estimates, but consistent with the conclusion that contacts to n-type layers are more noisy than to p-type GaSb layers. (It is also noteworthy, that lower noise is expected for higher doping density). In addition, theirs Au-Te based contacts are much better than ours In-based contacts.

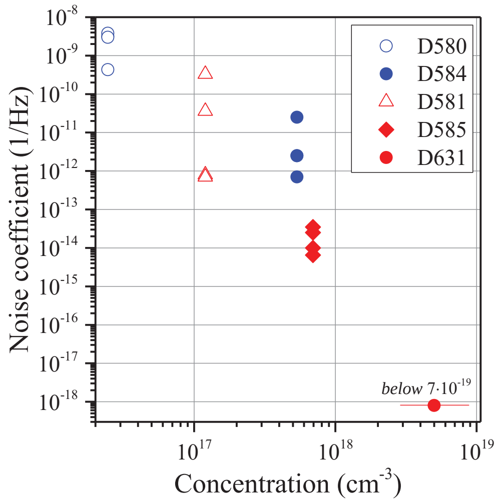

Fig. 4. Relative contact low frequency noise coefficient C_{lf} versus carrier density at temperature $T = 300$ K for layers with different doping type .

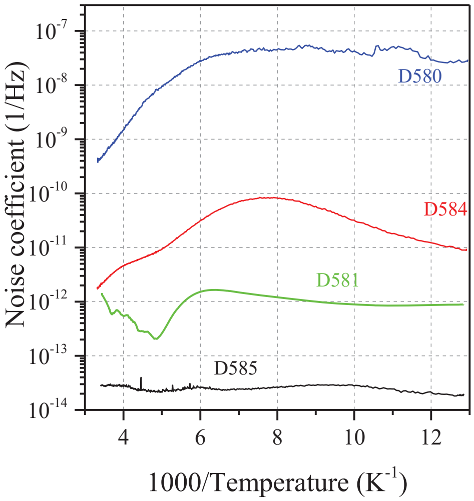

Fig. 5. Relative contact low frequency noise C_{lf} versus reciprocal of temperature for samples with different doping density/type.

B. *Low frequency noise of GaSb layer*

The estimation of layer-related component of lf noise is possible only with four-point probe measurements with separated current and voltage terminals for samples, which obey reciprocity rule (D584 and D585). As shown in Fig. 3b, in diagonal $AD_{CT}BC_{VT}$ or $BC_{CT}AD_{VT}$ configurations the quantity S_R is determined by the entire sample not only by near-contact areas. Thus, the layer-related component is more prominent in this configurations. Then, as the measured noise can be attributed to the entire layer the normalization of S_R by layer sheet resistance R_{sheet} is justified. In table II, the values of S_R at 1 Hz measured at 300 K and normalized quantity, $L_{lf} \equiv S_R/(R_{sheet})^2$ are gathered. The relative low frequency noise of the Be-doped layer is significantly smaller than that of Te-doped layer. As no lf noise was observed for sample D631 (Be-doped to 5×10^{18}) the conclusion is that the relative noise of the layers (L_{lf}) for p-doped samples decreases with the increasing doping concentration.

In ref. [11] N. Hooge et al. provided the value of parameter $\alpha_H = 3 \times 10^{-3}$ for p-type GaSb material. Then, the estimate of relative noise of homogeneous sample of volume V doped N_A is: $L_{lf} = \alpha_H/(VN_A) \approx 10^{-16}$ 1/Hz, if the values of V and N_D for sample D585 are used. This value can be viewed as the lower limit for measured lf noise. Our estimate is much larger due to current crowding effects, which make the effective volume much lower than V.

TABLE II. LOW FREQUENCY RESISTANCE NOISE FOR BERRYLIUM AND TELLLURIUM DOPED LAYERS

Sample	**Results at T = 300 K**		
	S_R (Ω^2/Hz)	R_{sheet} (Ω/sq)	L_{lf} (1/Hz)
D584 (n- GaSb)	1.1×10^{-8}	35	9×10^{-12}
D585 (p- GaSb)	2.3×10^{-10}	155	9.7×10^{-15}

IV. CONCLUSIONS

The resistance or non-resistance low frequency noise related to the contacts and the semiconductor layer can be qualitatively investigated by four point-probe method. Such measurements can be performed with the different terminal (contacts) configurations, which amplifies the noise coming from different regions of the sample/layer. The contact (metal/semiconductor interface) can be source of significant low frequency non-resistance noise. The relative contact lf noise (both resistance and non-resistance) is inversely proportional to layer doping concentration. For comparable doping densities the lf contact noise for n-type Te-doped GaSb layers are significantly larger than for p-type Be-doped layers. The lf noise related to the layer with similar doping level but different doping type is higher for n-type Te-doped layer. Nevertheless, both layers exhibited inhomogeneous distribution of the noise sources. The overall low frequency noise performance of highly Be-doped (>10^{18} cm^3) GaSb is very good: both contact and layer lf noise were not measurable.

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