BrainCom Deliverable D1.noise

Noise assessment of graphene field-effect transistors for monitoring local field potentials

WP	1	Technology of neural interfaces
Task	all	

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Deliverable abstract

This is a new deliverable suggested by the reviewers after the 1st year review. This deliverable is divided in two different parts. The first part details the current noise performance of graphene FETs, demonstrating that they are perfectly capable of monitoring local field potentials, and the second part is dedicated to summarize the planned technology programme to further improve the noise performance of graphene FET technology

This deliverable confirms that graphene FETs are perfectly suitable for being the active elements in the multiplexing scheme proposed in BrainCom, since they offer a suitable frequency response, sufficient noise performance, and low power.

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1. Introduction

This is a new deliverable suggested by the Experts Panel after the 1st year review. In their report the review panel recommended the following: “It is highly recommended to take a close look at the advancement of GFET noise reduction efforts, before it affects more workpackages. A new deliverable is required to specifically assess this point, with a deadline of 01/07/2018”

To address the recommendation of the review panel, this deliverable is divided in two different parts. The first part details the current noise performance of graphene FETs, demonstrating that they are perfectly capable of monitoring local field potentials (in the frequency range 1Hz to 150Hz), which are the brain signals to be monitored by the multiplexing device technology to be developed in BrainCom.

The second part of this deliverable is dedicated to summarize the technology programme which is implemented within BrainCom to further improve the noise performance of graphene FET technology; currently, the noise performance of gFETs can be summarized by the following noise figure of merit: 3 μV RMS for 100x100 μm^2 and 5 μV RMS for 50x50 μm^2 devices.

In summary, this deliverable demonstrates that despite the current graphene FET technology has not reached the ultimate performance in terms of noise (1 μV RMS, as suggested in the DoW), it is already capable of monitoring local field potentials with high enough fidelity; thus, no negative impact or delay is foreseen in the rest of the project. Yet, a technology programme is planned during the next 18 months to further improve the noise performance of graphene FETs, with the goal of getting closer to the ultimate performance limit.

2. Assessment of graphene FETs for in vivo monitoring of local field potentials

To evaluate the impact of the gSGFETs noise on experimental recordings, we have designed an experiment in which we have benchmarked the gSGFETs with state of the art Pt black electrodes.

To this end, epi-cortical probes fabricated with BrainCom gSGFETs technology have been used to perform *in vivo* experimental recordings of local field potentials (LFPs); *results are not published*. In the same experiment, an epi-cortical probe based on platinum black electrodes has been used to compare the recorded signals in the same experimental conditions. ***Figure 1*** shows the probe design, that consists on an array of 16 (4 x 4) gSGFETs (50 μm length, 100 μm width) spaced 400 μm. ***Figure 2*** shows the electrodes probe layout, that contains 16 gold electrodes with an electrodeposited Pt black coating. Platinum black electrodes has been used for benchmarking since they can be considered as the state of the art in terms of low impedance and low noise[1].

[1] C. Boehler, T. Stieglitz, M. Asplund, *Nanostructured platinum grass enables superior impedance reduction for neural microelectrodes*, Biomaterials 67, 346-353 (2015)

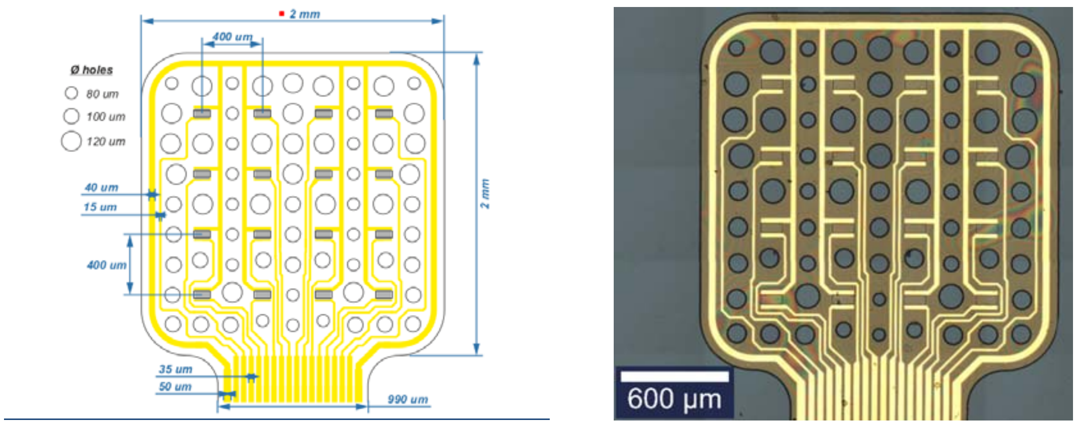


***Figure 1**. Left, schematic layout of an epi-cortical probe consisting of an array of 16 (4x4) gSGFETs. Right, optical image of the fabricated gSGFET epi-cortical probe.*

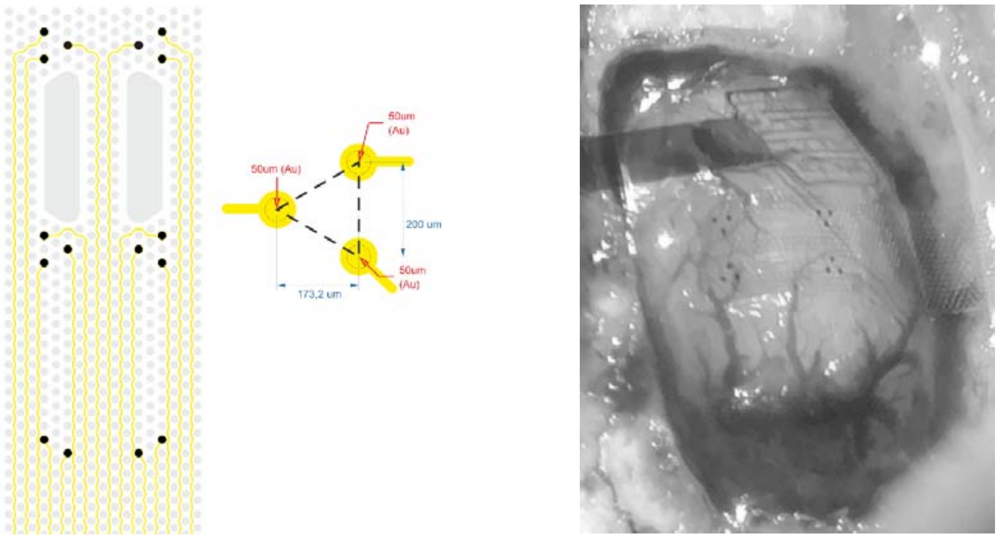


***Figure 2.** Left, schematic layout of an epicortical probe consisting of 16 platinum black electrodes. Right, optical image the experimental setup were it can be observe the probes placed next to each other in the same craniotomy.*

Experimentally, adult male Wistar rats (225-375 g) were used. Animals were deeply anaesthetized with ketamine. Body temperature were constantly monitored and maintained at 37ºC by means of a thermal blanket. A craniotomy and durotomy were performed on the left hemisphere over the primary somatosensory cortices in order to record with both surface probes. A Ag/AgCl electrode was inserted in temporal muscle and used as reference. ***Figure 2*** shows how both probes are placed next to each other in the same craniotomy.

The gSGFETs signals were recorded using a custom electronic instrumentation which provides current-to-voltage conversion and bias control for each channel[2]. It also allows to perform an *in vivo* DC characterization to obtain the transfer curve of each transistor, which is used to calibrate the

[2] B. M. Blaschke, N. Tort-Colet, A. Guimerà-Brunet, J. Weinert, L. Rousseau, A. Heimann, S. Drieschner, O. Kempski, R. Villa, M.-V. Sanchez-Vives, J. A. Garrido "*Mapping brain activity with flexible graphene micro transistors*", 2D Materials **4** (2), 025040 (2017)

recorded signals. Electrode signals were directly acquired by a commercial electrophysiological recording system consisting of a programmable gain amplifier (Multichannel Systems, GmbH) and digitizer interface (CED 1401 and Spike2 software, Cambridge Electronic Design, UK).

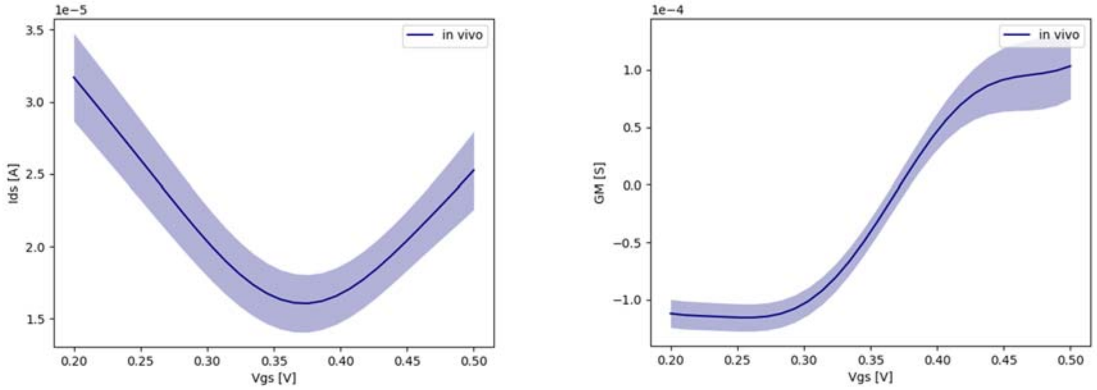


Figure 3*. Left, transfer curves (drain-source current vs gate-source voltage) of gSGFETs measured in vivo. Right, transconductance calculated from the in vivo transfer curve measurement. In both graphs, the solid lines indicate the mean value and shadow the standard deviation for the 16 transistors.*

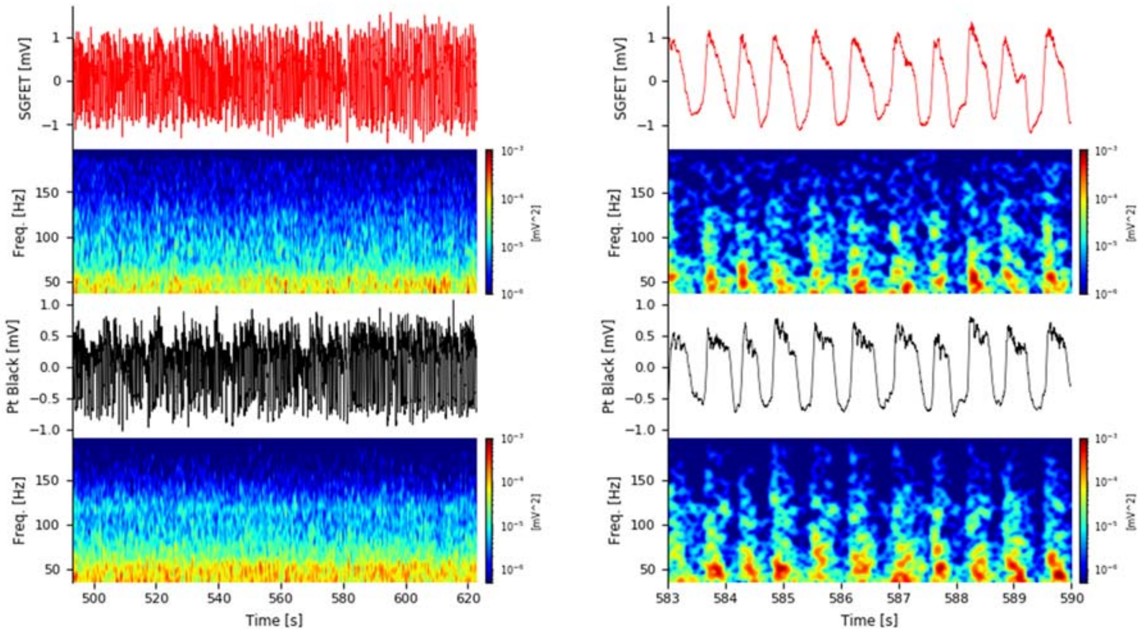


Figure 4*. Left, recording of spontaneous activity under ketamine anaesthesia with a gSGFET (red) and platinum black electrode (black). The spectrogram shows the power density frequency content as a function of time. Right, time zoom of the recording where it can be observed how the frequency content during the up-states are similar for the recordings of the transistor and the electrode.*

Figure 3 shows the characterization of gSGFETs performed *in vivo*. The measured transconductance for each channel is used to calibrate the recorded LFP signals. The spontaneous activity recorded under ketamine anaesthesia is shown in ***Figure 4***. The frequency content of signals as a function of time is depicted in the spectrogram plot. It can be observed an increase in the power of high frequency components (up to 150 Hz) in the Up-states of LPF recorded signals. It can be clearly observed how the frequency content of the signals recorded with gSGFETs and Pt black electrodes is similar

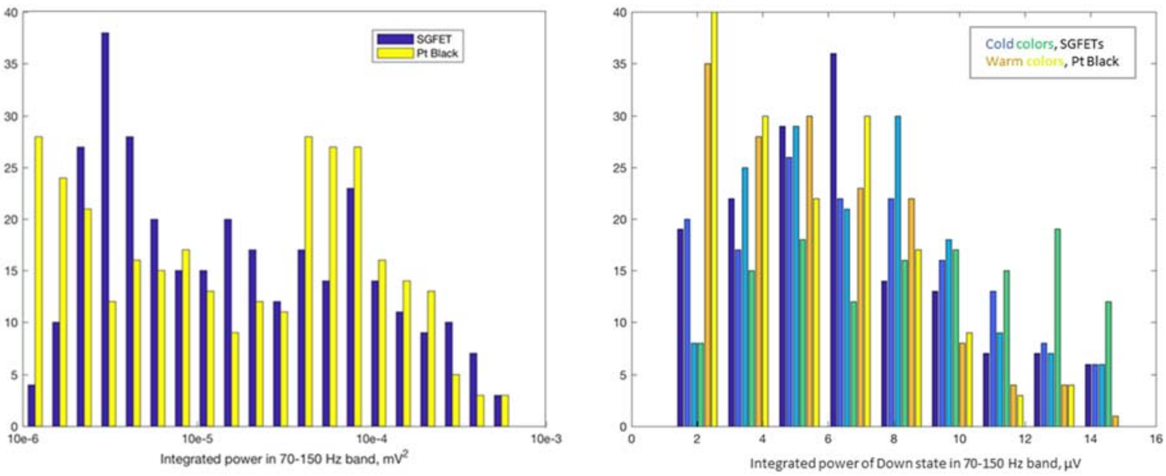


Figure 5. *Left, Distribution of integrated high-frequency (70-150 Hz) power for SGFET and Pt Black measurements obtained from the recordings in Figure 4. Right, Distribution of integrated high-frequency (70-150 Hz) power of the Down state for 4 graphene SGFETs (cold colours) and 2 Pt Black electrodes (warm colours).*

Figure 5 (left) shows a histogram of the high-frequency (70-150 Hz) power for the recordings with the gSGFET and the Pt Black devices shown in **Figure 4**, revealing a bimodal distribution of power associated with Up (high power) and Down (low power) states of the slow oscillation. The lower mode associated with the Down state can be used to gauge the level of noise as it is typically devoid of local high frequency activity. **Figure 5** (right) shows the histogram associated to the Down states recorded with 4 transistors and 2 electrodes. In this way, the noise floor of the SGFETs could be assessed in vivo as the value of the peak of the mode associated to the Down states, corresponding to ~5 μV RMS noise in the high-frequency band.

In order to get more insight into the performance of the sGFETS, several Vgs bias points have been experimentally evaluated aiming at reproducing the same behaviour observed in the characterizations using saline solutions. **Figure 6** shows the equivalent gate noise of the gSGFETs in the epicortical measured using a PBS solution; it shows the typical Vgs dependence which is related to the gate bias dependence of the transconductance and of the 1/f noise[3].

[3] C. Hebert, E. Masvidal-Codina, A. Suarez-Perez, A.B. Calia, G. Piret, R. Garcia-Cortadella, X. Illa, E. Del Corro Garcia, J.M. De la Cruz Sanchez, D.V. Casals, E. Prats-Alfonso, J. Bousquet, P. Godignon, B. Yvert, R. Villa, M.V. Sanchez-Vives, A. Guimerà-Brunet, J.A. Garrido, *"Flexible Graphene Solution-Gated Field-Effect Transistors: Efficient Transducers for Micro-Electrocorticography"*, Advanced Functional Materials **28**, 1703976 (2018).

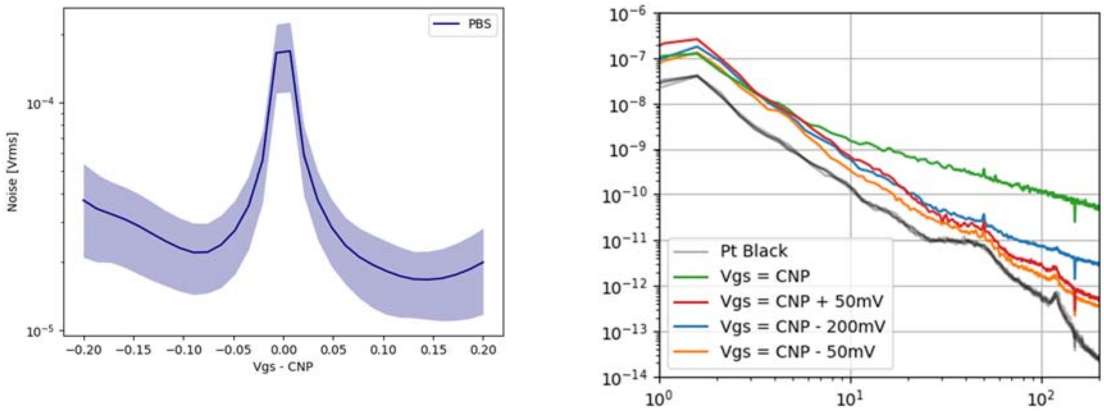


***Figure 6**. Left, equivalent gate noise measured in PBS solution presented in V RMS values, calculated using a bandwidth from 1 Hz to 1 kHz. Right, Power spectral density of the signals recorded with gSGFETs for several Vgs bias points (0.366 V is the CNP of the devices).*

The power spectral densities of recordings performed at 4 different bias points are shown in **Figure *7***; the figure also shows the PSD of recordings with the Pt black electrodes. As expected from the saline characterization, the recordings performed with a Vgs bias very close to the CNP of gSGFETs (Vgs = CNP) are clearly dominated by the intrinsic 1/f noise of the gSGFETs. In the same way, the recordings for a bias condition far away from CNP (Vgs = CNP – 200 mV) are slightly dominated by the intrinsic 1/f noise. In these two cases, the power of the biological signals is lower than the intrinsic noise of the gSGFETs, limiting the performance of the devices.

However, for the recordings performed at CNP ± 50 mV (Vgs = CNP ± 50 mV), the intrinsic 1/f noise is lower than the power of the biological signal, and the recordings with the gSGFETs provide the same information than in the case of the recordings with the Pt black electrodes, in the frequency range 1Hz to 150 Hz.

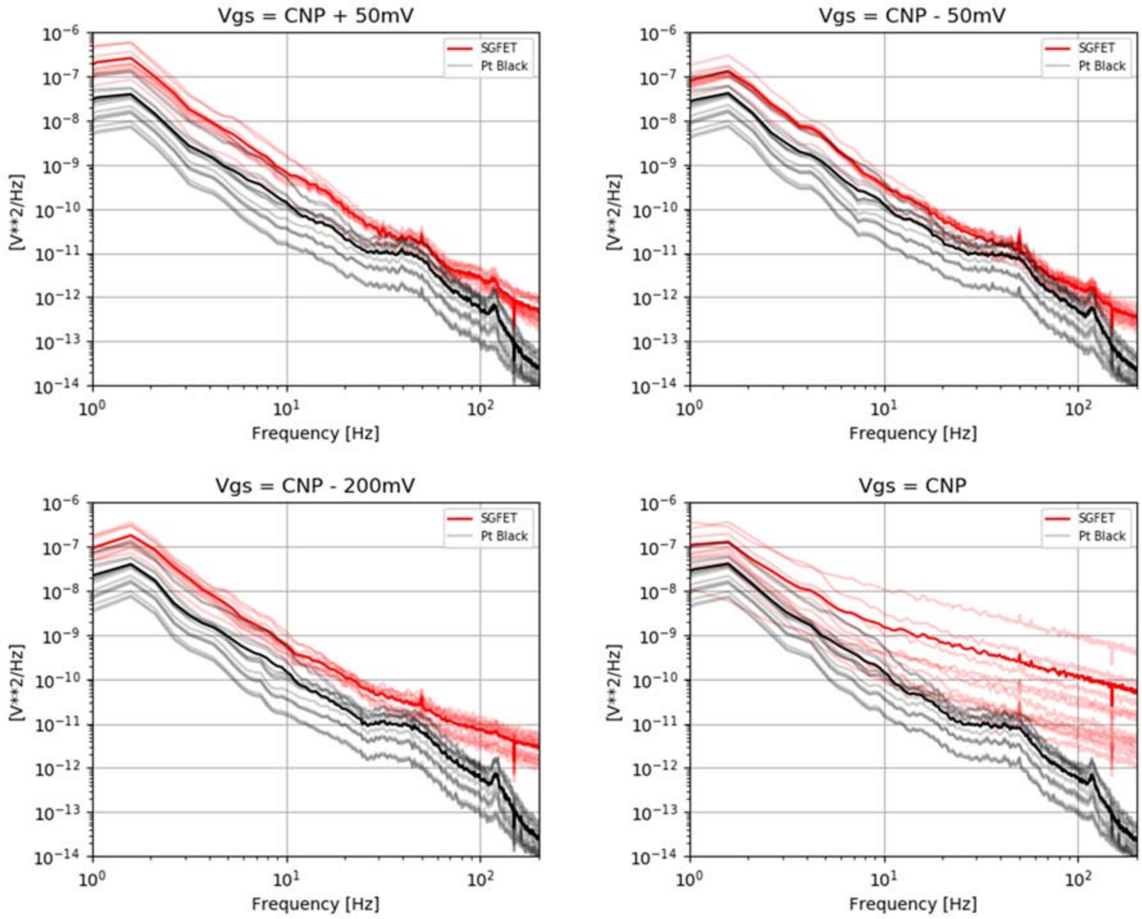


__Figure 7.__ Power spectral density for several bias conditions (in red gSGFETs and in black Pt black electrodes); the solid lines indicate the mean value for each group.

Recordings of spike-like test signals

The capability of gSGFETs to record high frequency signals (above 100 Hz) has been validated in vitro using a low noise signal generator provided by Multichannel Systems. The spike-like test signals (hippocampal population spikes) generated are acquired by the gSGFETs epi-cortical probes in PBS solution. **Figure 8** shows the recordings of 9 transistors in a gSGFET probe when a typical signal of a hippocampal population spike is generated and applied to the PBS solution. The right graph in **Figure 8** attests for the homogeneity of the recordings of the 9 transistors.

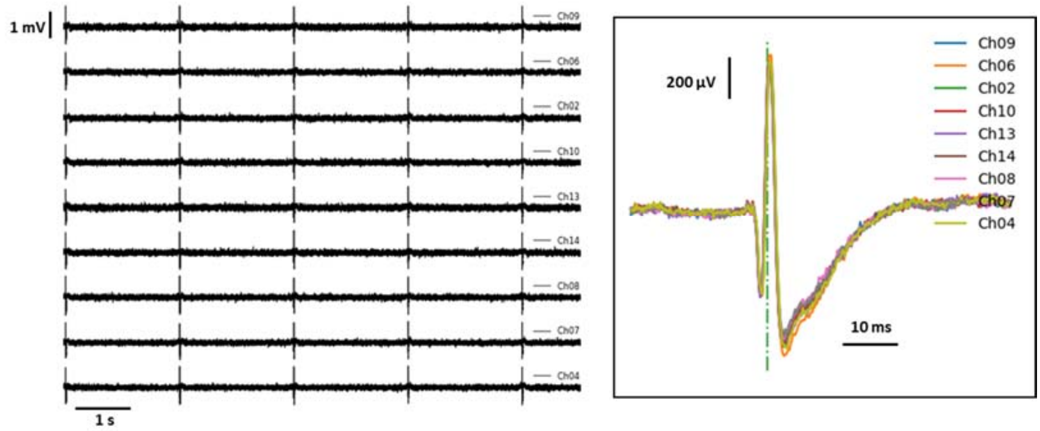


__Figure 8__. Spike-like signals (hippocampal population spike type) recorded by gSGFETs and generated by a MCS signal generator. The left graph shows a 10 seconds recording of 9 transistors. The right graph reveals the homogeneity of the recordings of one single spike by the all transistors.

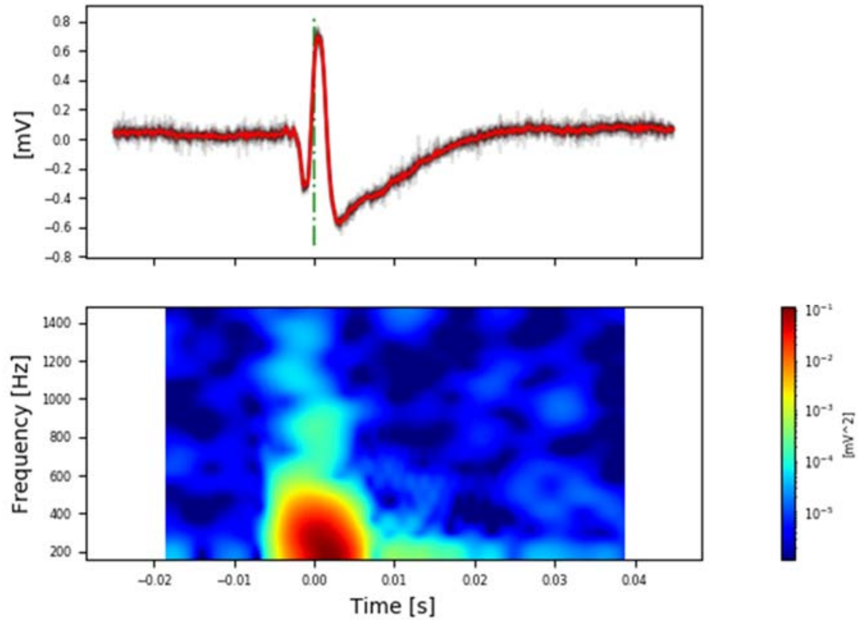


__Figure 9__. Top, 10 spike-like signals averaged, red line indicates the averaged signal and black lines are overlapping of the individual signals. Bottom, power spectral density of the averaged signal.

In order to assess the capability of gSGFETs to monitor the high frequency components of such spike-like signals, a spectrogram analysis is performed in which the power spectral density of the averaged (10 times) recording of one transistor is shown. The frequency content of signals as a function of time is depicted in the spectrogram plot of **Figure 9**, confirming that the gSGFETs can also monitor the high frequency components (above 1200Hz) of the generated spike-like signals.

3. Towards the ultimate noise performance of graphene FETs

In Section 2 we have demonstrated the suitability of the current graphene SGFET technology to monitor local field potentials, as well as high frequency spike-like signals. This information allow us to continue the BrainCom research program with full confidence about the suitability of the graphene SGFETs for the multiplexed ECoG technology.

However, we also acknowledge that the current graphene SGFET technology can be further improved to reach even lower noise levels to be able to detect low amplitude single unit activity and resolve spatial variations of power and phase in the high frequency oscillatory activity. Silicon technology has been improved for decades before it has reached its current low noise performance; graphene transistors offer at this stage, without decades of improvements yet, similar noise performance, indicating that there is still a lot of space for improving the graphene transistor performances.

We identified several sources of noise in graphene transistors, as discussed below. A dedicated work plan with different tasks is drawn (see Gantt chart below) to lessen the influence of each of these sources. One of these sources, namely the contact noise, is already under advanced investigations. So far, this study proved that contact and transistor geometry optimisation already allowed decreasing the intrinsic noise down to 5µV rms for 50x50µm^2 transistors (see Figure 9). This new developments will be exploited for the design of new probes and will be first tested *in vivo* by LMU from month 21 to 24 to assess and validate the new designs.

-Task Noise-1: Optimization of transistor geometry and electric contact technology: In our transistor configuration, the contact resistance has been found to be dominated by the sheet resistance of graphene under the metal (*manuscript in preparation*), allowing for the evaluation of correlations between the density of carriers and low-frequency noise at the contacts.

Work plan: The contact resistance will be studied in wafer-scale arrays of graphene solution-gated field-effect transistors with different contact designs in order to determine the dominant charge transfer path at the graphene-metal interface. In order to assess their relationship, the effect of the channel resistance on the contact noise as well as the contribution from the channel noise will also be taken into account. So far the experimentally-derived correlations indicate that contact noise originates from charge trapping-detrapping processes at the graphene-metal interface, presenting edge contacts as a promising approach to reduce contact noise. Finally, the obtained geometric relationships will allow to derive a set of device design rules to minimize the impact of contact noise and achieve optimized signal-to-noise ratios.

By reducing the overlapping between the metal contact and the graphene channel, and choosing a square geometry for the transistors, the intrinsic noise of the transistors can be reduced. For instance, in the band with from 1Hz to 100Hz, was obtained on 5µV rms for 50x50µm^2 transistors **Figure 10**. A clear dependence of the intrinsic noise with the active area of the transistor exposed to the liquid (**Figure 10**) is also revealed.

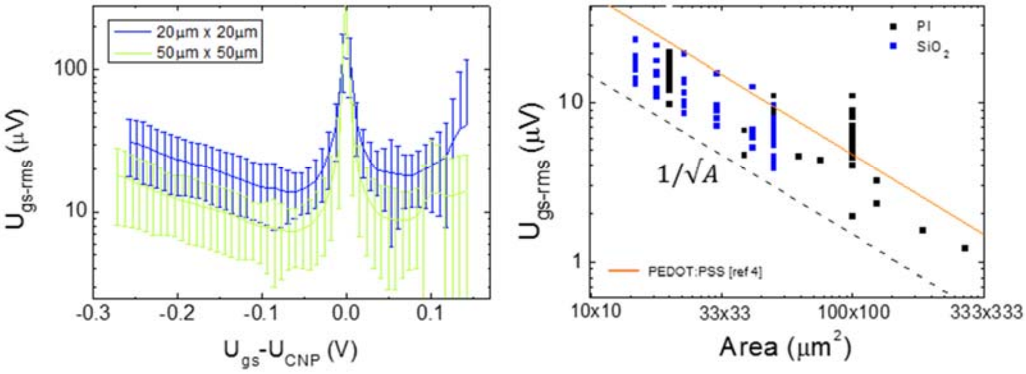


Figure 10*. Left, gate bias dependence of the equivalent gate noise measured in PBS solution presented in V_{RMS} values, calculated using a bandwidth from 1 Hz to 100Hz (typical LFP bandwidth) for two different transistor active areas. Right, minimum of the equivalent gate noise calculated for a large number of graphene SGFETs with different active areas, comparing gSGFETs fabricated on polyimide (PI) and SiO_2 substrates. The black dashed line represents a $1/\sqrt{Area}$ dependence. The orange solid line correspond to the noise data of PEDOT:PSS OECTs discussed by Stoop et al.[4].*

- Task Noise-2: Improvement of clean room processes: During the technology processes for the fabrication of graphene SGFETS, the CVD graphene layer is in contact with many resists and undergoes harsh processes such as reactive ion etching and iron chloride etching. Thus, similarly to the substrate that can introduce charge impurities, resist residues can also introduce charge traps that lower the mobility of the graphene channel and increase the noise in the channel. Resist residues should be carefully removed without affecting the graphene layers.

Work plan: A careful study of the impact of the technology processes will be performed. This includes the choice of the resists to be in contact with the graphene but also the adjustment of the etching parameters. The resist should not degrade the graphene and should be easy to remove to avoid any residues at the surface of the graphene. To reach this requirement, the cleaning of the current resist used for the fabrication of the transistor will be studied. Several solvents will be used. They should dissolve completely the resist residues while avoiding any degradation of the graphene. Furthermore, the etching parameters will be carefully studied to avoid hard baking of the resist at the surface of the graphene channel. This study will be conducted using Raman spectroscopy to assess the presence of residues as well as the quality of the graphene. The noise of the graphene transistor will be correlated to the results obtained by Raman spectroscopy.

- Task Noise-3: Influence of substrate: The substrate for the fabrication of graphene SGFETs has been identified as an important source of noise (see **Figure 10**). The roughness and the impurities

[4] R. L. Stoop, K. Thodkar, H. J. Bolink, C. Schönenberger, M. Calame, *Charge noise in organic electrochemical transistors, Physical Review Applied 7, 014009 (2017)*

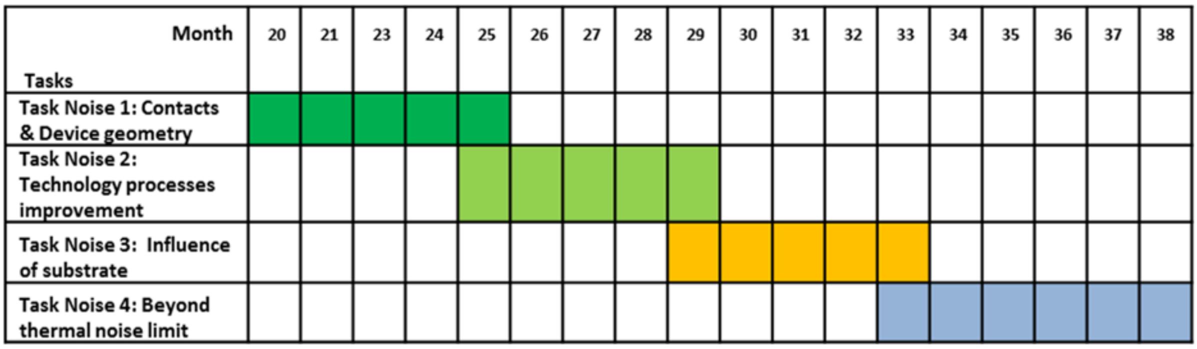
are sources of charge traps that induce noise in the channel. So, underlying insulating materials will be investigated in term of roughness and low interaction. The influence of these parameters will be carefully studied. Underlying substrate such as ultralow roughness Al_2O_3, or MoS_2 will be used. These materials are available within the BrainCom consortium (ICN2, CSIC and UCAM).

Work Plan: A systematic study will be performed to evaluate the reduction of the noise using ultrasmooth Al_2O_3 or MoS_2. The Al_2O_3 will be deposited by atomic layer deposition (ALD) and the MoS_2 with very low carrier mobility will be grown by MOCVD and deposited on the wafer by transfer. The evaluation of the roughness will be performed using atomic force microscopy (AFM). The noise assessment will be done using the dedicated electronic system developed by ICN2 and the CSIC.

- Task Noise-4: Beyond the thermal noise limit: The thermal noise at the graphene/electrolyte interface can set the ultimate limit of graphene SGFETs; typically, this thermal noise is related to the leakage resistance at the graphene/electrolyte interface as well as to the interfacial capacitance[5]. Both parameters can be engineered by using multi-layer graphene films (for instance, by stacking several single layer graphene films on top of each other), which can mitigate the influence of the graphene-liquid interface. In this configuration, the first layer in contact with the graphene is used as a first charge screen so that the underlying layer modulate the conductivity of the channel with less fluctuations that occurs at the liquid –graphene interface[6]. In the case of three layers or more, the layers in contact with the substrate can also screen the carriers' trapping-detrapping phenomenon occurring at the graphene-substrate interface.

Work plan: In order to assess the impact of the thermal noise, multi-layer graphene SGFETs will be fabricated and their noise performance investigated. The multilayer film will be obtained by multiple transfers of single layer graphene.

Gantt chart summarizing the tasks associated to the noise reduction work plan



At months M29 and M38, reports will be submitted to the Steering Committee for their assessment.

[5] M. S. Crosser, M. A. Brown, P. L. McEuen, and E. D. Minot, "*Determination of the Thermal Noise Limit of Graphene Biotransistors*," *Nano Lett.*, 15, 5404–5407 (2015)

[6] A. N. Pal and A. Ghosh, "*Ultralow noise field-effect transistor from multilayer graphene*," *Appl. Phys. Lett.* 95, 082105 (2009); Y. Sui and J. Appenzeller, "*Screening and Interlayer Coupling in Multilayer Graphene Field-Effect Transistors*," *Nano Lett.* 9, 2973–2977 (2009)

4. Conclusion

In conclusion, this deliverable demonstrates that current graphene FET technology is already capable of monitoring local field potentials with high enough fidelity; thus, **no negative impact or delay is foreseen in the rest of the project**. Yet, with the goal of getting closer to the ultimate performance limit of graphene, a technology programme has been designed and will be implemented during the next 18 months to further improve the noise performance of graphene FETs.

This deliverable confirms that graphene FETs are perfectly suitable for being the active elements in the multiplexing scheme proposed in BrainCom, since they offer a suitable frequency response, sufficient noise performance, and low power.