Fabrication of a 3 GHz Oscillator based on Nano-Carbon-Diamond-Film-Based Guided Wave Resonators

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INTRODUCTION

A lot of work already has been dedicated to evaluate the interest of Diamond-like Carbon films for the development of high frequency surface acoustic wave (SAW) devices for various Radio-Frequency (RF) applications [1, 2]. The main interest of such a material consists in its very high acoustic phase velocities, typically ranging from 12 to 9 km.s^{-1} when used as SAW wave guide. The absence of any piezoelectric properties of this material however requires the use of a piezoelectric film to excite and detect the waves. As a consequence, the quality of the final device exploiting such material is directly affected by the quality of the piezoelectric layer and the diamond layer as well. Until now, rather modest values of quality coefficient of SAW resonance on such layered substrate has been reported and only a few studies have been devoted to comprehensively understand the actual limit of these devices and how to overcome the corresponding limitations.

In this work, we have investigated the possibility to use carbon-diamond layers exhibiting nano-sized grains for the fabrication of SAW guides and more particularly resonators based on such materials. One of the main purpose of this work was to check the influence of the grain size on the quality of resonator spectral signature and to evaluate the possibility to fabricate high frequency sources along this approach. We have investigated various material combinations, i.e. Aluminum Nitride (AlN), Zinc Oxyde (ZnO) and Lithium Niobate ($LiNbO_3$) deposited using sputtering techniques on Nano-Carbon-Diamond (NCD) layers grown along different techniques (nano-seeding, BEN, followed by MPCVD). The different NCD and piezo-layer deposition approaches are described and the main characteristics of each material is presented. We found that the best configuration was based on ZnO/NCD material combination provided the piezoelectric layer was deposited on the so-called nucleation surface of the NCD, i.e. the diamond is grown first on a rather thick substrate and then separated from its growing support, yielding a self-supported diamond substrate and an access to the above mentioned surface. Numerous resonators have been fabricated on such substrates, allowing for characterizing and exploiting resonance near 3 GHz. An oscillator then was built using such a configuration, but using directly the tip probing conditions instead of dicing and packaging the final device (an operation rather complicated when using self-supported diamond). The stability of the oscillator has been measured near 10^{-7} and its phase noise was found near -100 dBc at 10 kHz. These values are explained by the fact the resonator first was not optimized for the exploited mode and operating frequency and second significant noise contributions were added by the oscillator loop itself. Consequently, large improvements can be expected along the proposed approach.

In the first section of the paper we briefly recall the chosen waveguide configuration, showing the dispersion analysis used to design the resonator. We shortly report information about the NCD, the piezoelectric film and the E-beam process. Characterization results of single-port resonator test vehicles also is presented. Finally, the fabrication and characterization of the 3GHz oscillator is described in detail and discussed as a conclusion.

DESIGN OF DIAMOND-CARBON-BASED SAW DEVICES

Analysis of dispersion behavior

We present first the typical geometry we considered in that study. Although many configurations can be achieved, we have only considered the simplest one as we intend to actually implement the designed devices. We then had to avoid tricky material combinations requiring numerous etching and/or deposition steps that may prevent the achievement of test vehicles. Figure 1 shows the selected structure and defines axis orientations and layer dimensions.

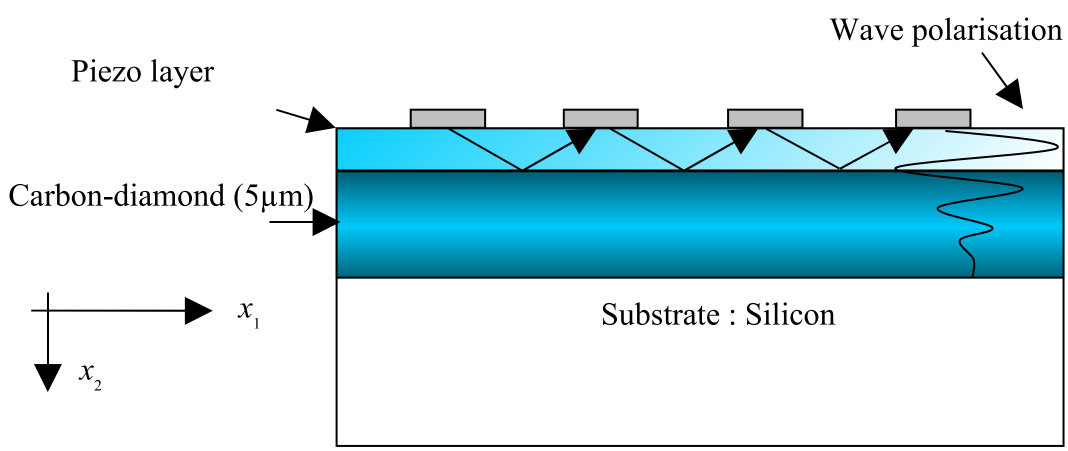
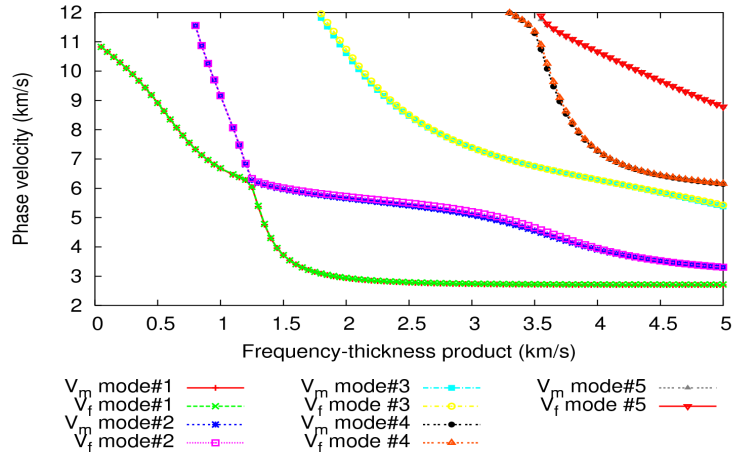


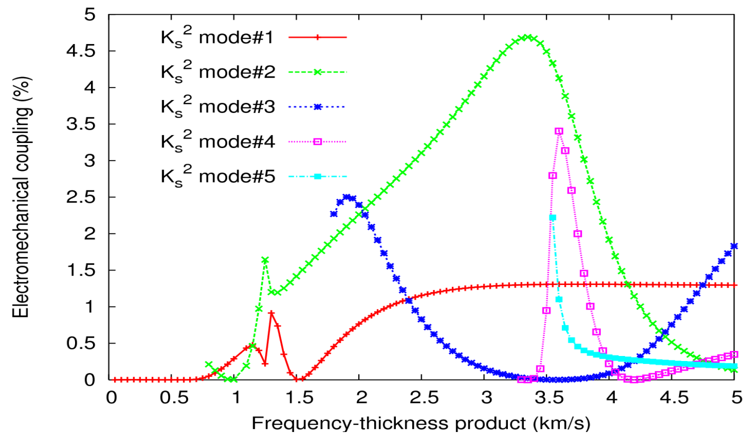
Fig.1 Typical waveguide configuration considered for the dispersion analysis. The carbon-diamond layer is fixed to 5µm, the silicon substrate is assumed semi-infinite and the piezo-layer thickness is varied to check the best operating point.

Three different piezoelectric layers have been considered to excite and detect the guided waves, i.e. C-axis-oriented AlN, ZnO and $LiNbO_3$. As Zinc Oxyde was the material exhibiting the most interesting experimental behavior, we mainly focus on ZnO/NCD/Silicon compounds (other results can be found in [3]). We then compute the principal wave parameters from the effective permittivity of the material stack top surface. Only non-leaky waves are considered in the present study as we expect to reduce as much insertion losses of final devices. Dispersion curves for the selected material configuration are reported in fig.2

We have selected the most favorable operating point considering the following criteria: highest electromechanical coupling, mode purity, smallest velocity dispersion (when possible). We then expect to use mode #3 with a frequency.thickness product between 1.75 and 2.25 km.s^{-1}, yielding a ZnO thickness of 0.45µm to operate near 5GHz. The NCD thickness is fixed minimum to 5µm for a n efficient acoustic shielding of the Silicon substrate.



(a)



(b)

Fig.2 Dispersion curves for the ZnO/C-D/Si configuration (a) wave velocity (b) electromechanical coupling.

Propagation under periodic grating

We used our Finite Element/Boundary Element Model (the so-called FEA-BIM [3]) to simulate the wave propagation under periodic aluminum grating and to derive mixed matrix parameters for optimizing the resonator structures. Particularly, we have studied the evolution of the phase velocity, electromechanical coupling factor, reflection coefficient versus the electrode shape along the analysis procedure described in [4]. Contrarily to the case of semi-infinite substrate, the actual material stack and targeted working frequency must be considered for this analysis. Hence, the identified optimal electrode shape is specific to the considered configuration. The electrode relative height and metal ratio then are deduced from the corresponding dispersion curves and reported in Table 1, together with the expected propagation characteristics of the wave.

Table 1 Mixed matrix parameters vs material configurations

Piezo layer	period (µm)	Electrode h/λ (%) a/p	Velocity ($m.s^{-1}$)	K_s^2 (%)	Reflection (%)
ZnO	1.04	5.0 0.65	10191	0.87	–12.3

Mixed matrix simulation

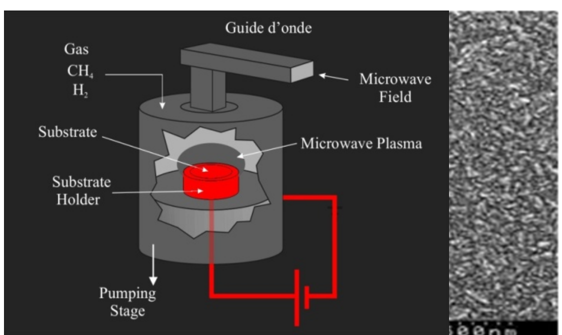
Both single and double-port devices have been considered for this design step. Fully synchronous devices and Hiccup structures have been simulated for the different previously presented material combinations. Very optimistic results have been obtained using parameters of Table 1, as we did not access any reliable information concerning material losses for the NCD and the piezo-layers as well. The only important feature here was to adapt the Hiccup structure to negative reflection mirrors. The number of finger pairs in the transducers was set to 100 to favor a maximum signal dynamics. Mirror are typically composed of 200 electrodes again to promote the maximum wave reflection efficiency. The aperture was fixed large enough to avoid any diffraction effect. These figures were also found compatible with reasonable (about one hour long) E-beam process duration.

EXPERIMENTAL IMPLEMENTATION

The optimized parameters have been considered for the fabrication of resonators operating near 5GHz. Since material samples were quite small (a few cm^2), we were obliged to use electron beam (E-beam) lithography to allow for a reliable fabrication of sub-micron patterns. We briefly describe typical feature of NCD as well as the E-beam writing process and we show some examples of resonators. For each kind of devices (single and double port), we show experimental results assessed by theoretical predictions.

NCD growth on silicon

Nano Carbon Diamond layer are particularly grown along Microwave Plasma assisted Chemical Vapor Deposition (MPCVD). 3 type of gases are exploited, namely Ar, H2 and CH4. Various surface preparation have been investigated in this study and optimal seeding conditions have been pointed out to optimize the grain size. The preferred operating conditions correspond to high plasma powers (from 600 to 1100W) and a quite high chamber temperature (800 to 100°C). Fig.5 shows a principle scheme of the reactor and a SEM view of a 5µm thick NCD overlay. Although rather small roughness were obtained (~25 nm RMS), we finally preferred to operate with nucleation surfaces to meet optimal E-beam lithography conditions.



(a) (b)

Fig.3 NCD growth (a) principle of the MPCVD growing chamber (b) SEM view of a NCD film grown using a 10% CH4 plasma.

E-beam writing technology

We briefly describe here the implemented E-beam process to achieve reliable test vehicles. It consists in 8 successive steps as follows:

- Sample cleaning using an O2 plasma
- Resist spinning (260 nm thick PMMA)
- conductive layer deposition (15 nm thick Cr, charge evacuation)
- E-beam exposure (deposited dose 130 – 200 µC/cm^2 at 15kV acceleration field)
- Cr removing (15 s Cr etch)

- Resist development (MIBK/IPA 1/3, rinse in IPA)
- Al deposition (evaporation 50 to 100 nm)
- Lift-off (resist remover) and std device cleaning

The energy dose is optimized for each kind of sample. 20 to 30 resonators are typically built on a given sample, yielding statistical assessment of the device operation.

Single port resonators

Figure 4 shows SEM views of a synchronous single port resonator. Most fabricated devices have revealed defect free and have been measured. Figure 5 shows typical results on ZnO based substrates. The theory assessment has allowed to point out a ZnO thickness twice smaller than the expected one. The results are reported for AlN based substrates. Here again, a slight thickness drift (0.38µm for a 0.55 µm target) has been revealed by the analysis. Whatever, these results show that the films operate well enough to allow for a reliable analysis of the obtained results.

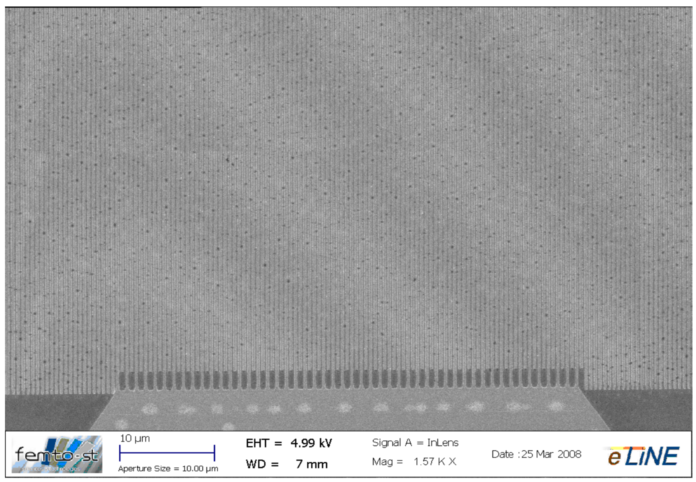


Fig.4 SEM view of a single port resonator (near the pad)

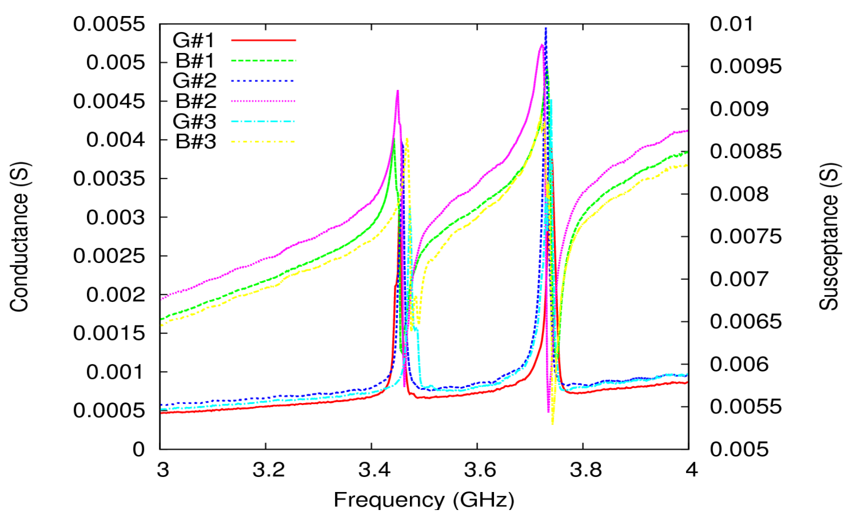
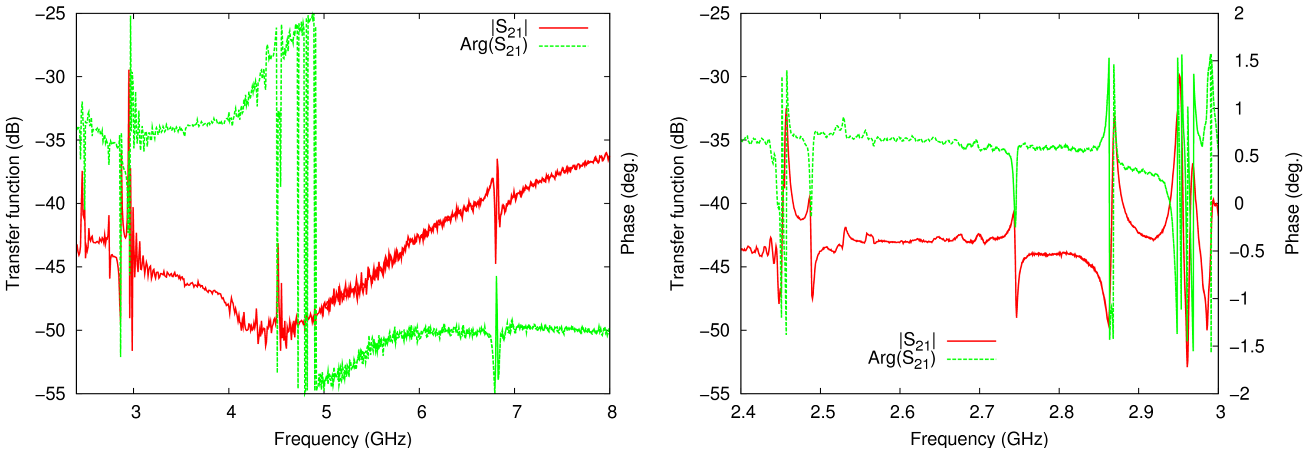


Fig.5 Measured admittance for the ZnO-based resonators

Double port resonators

As the phase rotation was quite small for single port resonator and the parameters to adjust a negative-resistance-based oscillator hardly achievable in practice, we have implemented double port resonator with the hope to get rid of these difficulties and to allow for the fabrication of a feed-back oscillator, much simpler to achieve. Figure 6 shows an example of such a device built on ZnO which finally was found the most adapted film in terms of response dynamics for the tested samples, even if the film thickness was far from the targeted one. In that case, the IDT were composed of 50 finger-pairs, the grating mirrors composed of 200 electrodes. The period was fixed to 1µm for an electrode width of about 600nm. The cavity was 20.5µm long, allowing for the resonance to be located near the center of the stop band.



(a) (b)

Fig.6 Example of double-port resonator transfer function (a) wide spectrum (b) zoom near the 2 first modes

Although the response dynamics remains rather small and the insertion losses notably high (about 28 dB), we decided to build an oscillator stabilized using the end-of-th-stop-band resonance of the second mode. As we did not manage the NCD substrate dicing, the connection between the resonator and the phase-locking electronics was achieved via tip probing, which yield notable cable length imposing a 45 dB amplification to meet the Barkhausen conditions. Figure 7 shows the oscillator scheme and the corresponding components nomenclature.

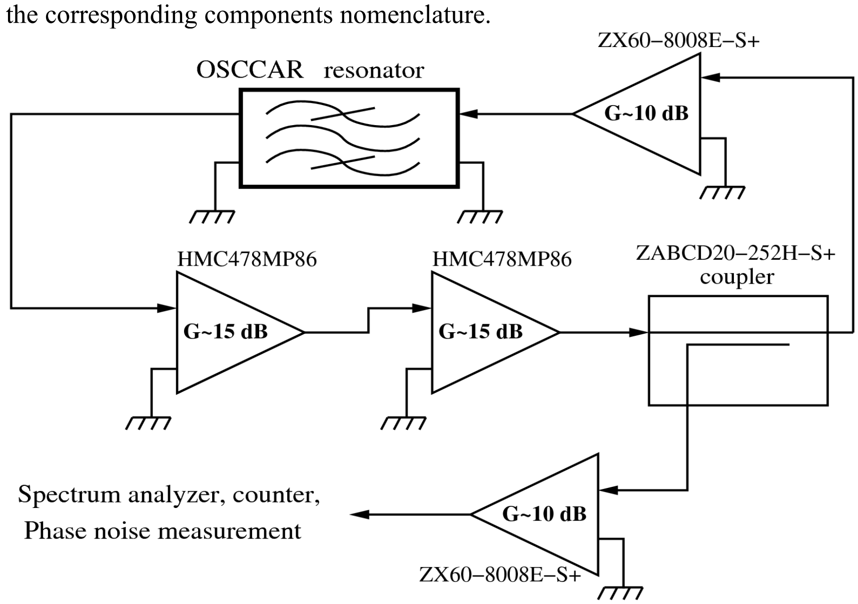


Fig.7 Scheme of the implemented oscillator

Figure 8 shows the phase noise measurement for this oscillator. The typical noise figure at 10 kHz is found near -100 dB. Deducing the loaded quality factor Q of the resonator from this result yield a value of many thousands whereas experimental characterization provides a value of about one thousand. This seems to indicate the large part of the amplifier loop to the phase noise. One can also evaluate a short term relative stability from this phase noise measurement which yields a value of 3.10^{-9} for 1s. This estimation is achieved considering a continuous $1/f^3$ slope until 1 Hz, which appears a bit hypothetic accounting for the thermal sensitivity of the exploited mode (near –40 ppm.K^{-1}). One should better keep in mind a value of 10^{-7} for 1s. experimentally observed (fig.9), which should notably be improved without too much efforts.

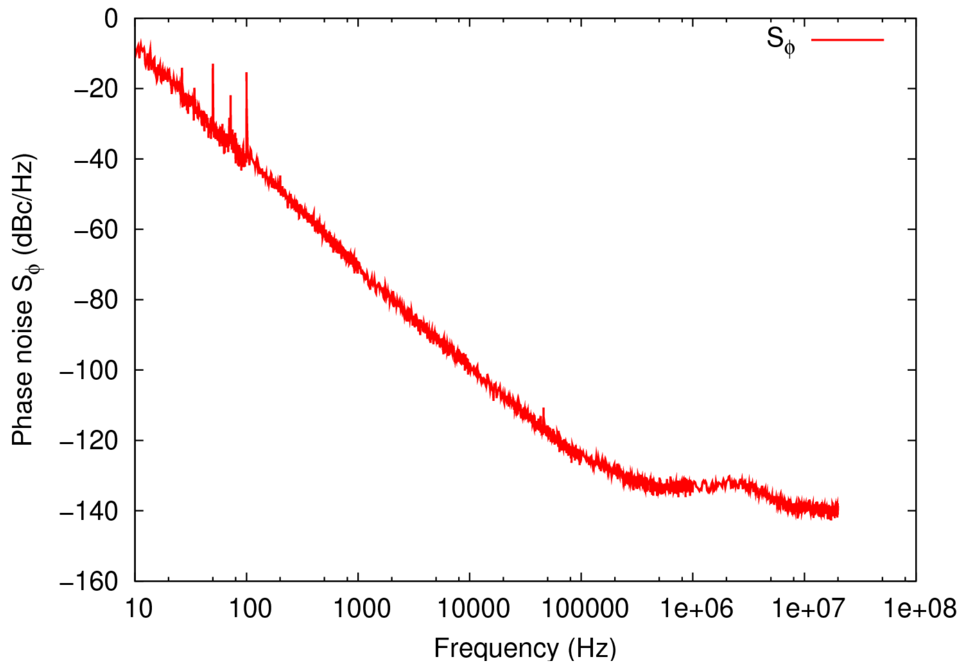


Fig.8 Phase noise measurement of the oscillator

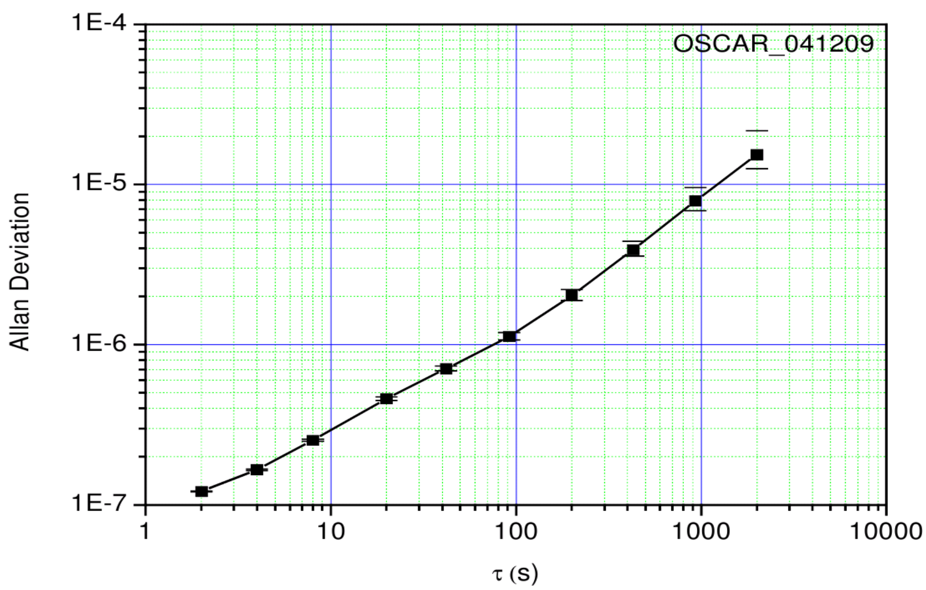


Fig.9 Short term stability of the oscillator (Allan variance)

CONCLUSION

In this work, we have developed high frequency resonators for frequency source applications. These resonators were built using E-beam lithography on ZnO/NCD/Si substrate, exploiting the nucleation side of the NCD to allow for a reliable and reproducible lithography step. NCD films and substrates have also been used to minimize the acoustic losses due to large grain overlays favoring acoustic diffusion along the surface propagation. Single and double port resonators have been built in the 3-6 GHz frequency range. Double port resonators have revealed compatible with the oscillator application, yielding a first oscillator demonstration near 3 GHz. Considering the operation condition of this oscillator, one should improve the corresponding stability characteristics without too much efforts, simply developing an adapted packaging of the resonator and a robust low noise amplifier loop.

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