Synchrotron-like THz emitters based on corrugated graphene

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***Abstract* — Here, we show that corrugated graphene with sub-µm period has the potential to generate synchrotron-like radiation in the THz frequency range. We perform electrodynamic calculation with a model of charges in periodic angular motion and demonstrate that significant output power levels can be obtained as well as geometrically tunable THz frequencies. We also report on the first technological fabrication of corrugated hBN-encapsulated graphene devices for synchrotron-like THz emission. We perform low-bias transport measurements at 4 K and show interesting deviation from transport in usual plane graphene.**

I. INTRODUCTION

SYNCHROTRON-LIKE radiation process is well established in the context of vacuum electron-beam devices but represents an original concept for light emission in condensed matter [1,2,3]. Geometrical constraints such as corrugation of 2D-materials can be used to obtain radiation via angular motion making corrugated graphene an attractive concept to generate synchrotron-like radiation in the THz frequency range. Indeed, by applying a dc-voltage in the direction of the corrugation, charge carriers are forced to move through a periodically modulated trajectory. Therefore, they undergo periodic angular motion and correspondingly generate a synchrotron-like radiation (as illustrated in Fig. 1). Graphene is very attractive for this concept: due to its single-atomic layer thickness, conformal adhesion can be expected. Moreover, its high carrier velocity should provide a high output THz power, which evolves in v_0^4.

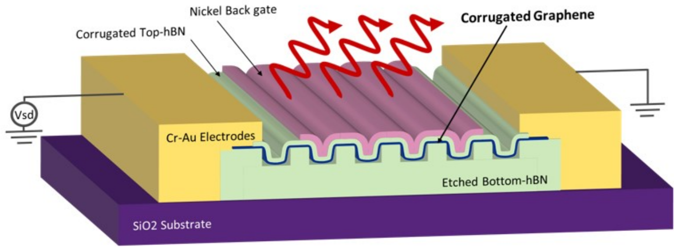

Fig. 1. Schematic view of the synchrotron-like THz emitter based on corrugated hBN/graphene/hBN device

II. RESULTS

In the effort of realizing a synchroton-like THz emitter based on corrugated graphene, we first develop a model of charge transport in angular motion for an arbitrary corrugation profile, so that we will be able to apply to our devices. The electron velocity is assumed to be constant in the graphene sheet. Thanks to this property it is possible to calculate numerically the bijection between time (t) and the electron position (x) for any kind of profile. We use classical electrodynamics in the electric dipole approximation to study the radiation properties of charges in periodic angular motion. We can apply Larmor formula and find the Poynting vector at any time, from which we deduce the output power, its spectral decomposition and its temporal average.

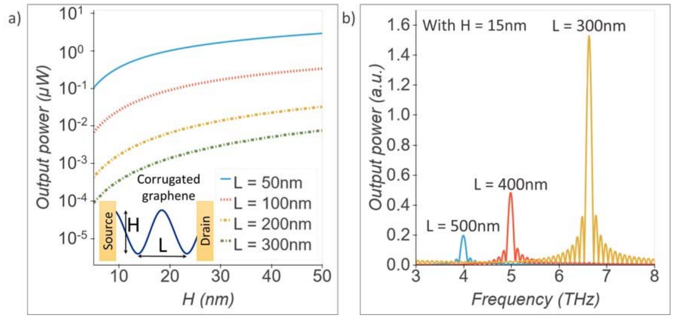

Fig. 2. a) Output power as a function of the corrugation geometrical parameters H and L b) Spectral decomposition of the output power for sinusoidal corrugations of various periodicities and amplitude 15nm in ballistic regime with $v_f=10^8$ cm.s^{-1} the Fermi velocity and $n_0=10^{12}$ cm^{-2} for the electronic density

In Fig.2, we study a realistic 50µm by 50µm graphene corrugation. We take the example of a sinusoidal profile of period L and amplitude H. We observe that by choosing the geometrical parameters of the corrugation profile during the fabrication process, the frequency in which the device mainly radiates can be tuned and the output power can be adjusted. For L=50nm and H=40nm we obtain an output power of 2.3µW

Our strategy to ensure high quality graphene, which is needed to maximize the output power, is to fully encapsulate

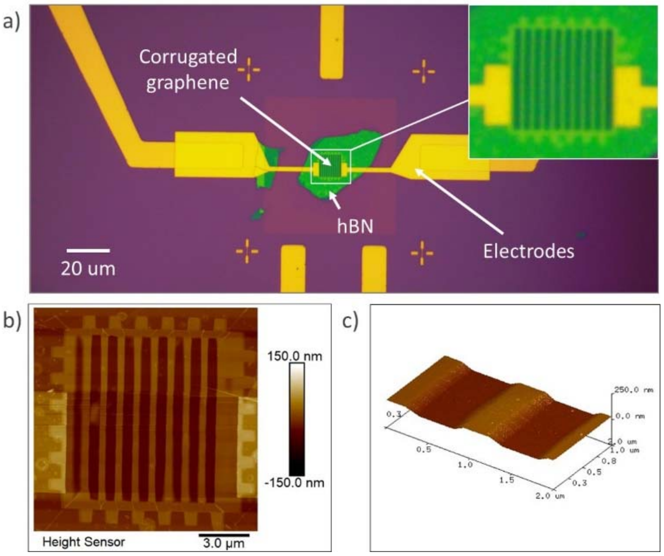

Fig. 3. Fabrication – a) Optical image of an encapsulated corrugated graphene. b) AFM image of the corrugation c) Detail of the corrugation - AFM 3D profile

the corrugated graphene. Thus, we fabricate corrugated hBN-graphene-hBN heterostructures. We etch trenches in an exfoliated h-BN flake using e-beam lithography and reactive ion etching (see Fig 3a) on which we transfer exfoliated graphene and thin h-BN flakes to obtain an encapsulated corrugated graphene (Fig 3b). Then we contact the graphene with 1D "edge contact" to design source and drain and add a gate (back- or top- gate) to control the carrier density (Fig.1).

We investigated this device by performing low-bias transport measurement at 4K as reported in Fig. 4. Gate dependent-resistance measurement (Fig 4b) shows unexpected behaviour when compared with similar measurements in flat monolayer graphene. The charge neutrality area forms a plateau and we observe shoulders on both sides of this plateau. These unique tendencies are assumed to be due to the non-uniform doping in the corrugated graphene layer created by the back gate. Indeed, the distance to the gate electrode varies along the corrugations, hence there will be accumulation of electrons in the lowest graphene parts and charges depletion in the highest ones (Fig 4d). The current-bias characteristics present super-linear evolution that is characteristic of Zener-Klein tunnelling current [4,5] with I_{ds} proportional to $V_{ds}{}^{\alpha}$ with α in]1, 1.4] (Fig 4b). Moreover, the non-linearity increases with the doping, which can be explained as well by the non-uniform doping. The more the graphene is doped, the more the charges will accumulate in the lowest regions, forming PN-like junctions with the highest depleted parts. Zener-Klein tunnelling is expected to happen more likely in these junction regions. These experimental observations are under investigation.

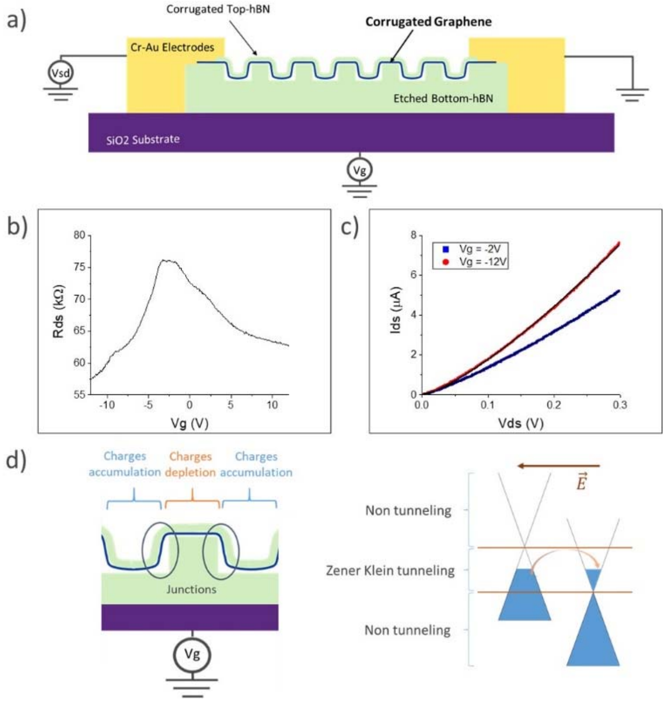

Fig. 4. Transport measurement a) Measurement principle b) Low-bias resistance measured at 4 K and V_{ds}=100 mV c) Current bias characteristic (symbols) measured at 4 K for V_g=-2V (blue square) on the Dirac plateau and at Vg=-12V (red circle) out of the plateau. The Zener–Klein tunneling current with I proportional to V^{α} is shown as black line with α=1.24 for V_g=-2V and α=1.32 for V_g = -2V d) Schematic view of the non-homogenous doping in the corrugation and of Zener Klein tunneling process

CONCLUSION

In conclusion, our work demonstrates the potential of corrugated graphene as a new type of room temperature compact THz emitters. We fabricated an hBN-encapsulated corrugated graphene and performed transport characterization at low temperature. We show unexpected electrical responses when compared to flat monolayer graphene, that are currently investigated.

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