Terahertz excitations in HgTe-based field effect transistors

A. Kadykov, C. Consejo, F. Teppe, W. Desrat, L. Viti, M. S. Vitiello, D. Coquillat, S. Ruffenach, S. Morozov, S. Kristopenko, M. Marcinkiewicz, N. Dyakonova, W. Knap, V. Gavrilenko, N. N. Michailov, S. A. Dvoretskii

1Laboratoire Charles Coulomb (L2C), UMR 5221, GIS-TERALAB, CNRS-Université de Montpellier, Montpellier, F-France
2Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, Russia
3NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy
4Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, pr. Akademika Lavrent’eva 13, Novosibirsk, 630090 Russia
Email : Christophe Consejo@univ-montp2.fr

Abstract. We report on Terahertz detection by inverted band structure HgTe-based Field Effect Transistor. Photoconductivity measurements allow for the observation of cyclotron resonance and Shubnikov-de-Haas-like oscillations. However, an unexpected peak was observed at the critical magnetic field value for which zero mode Landau Levels are crossing. Therefore, this specific feature of Terahertz photoconductivity spectra can tentatively attributed to this magnetic field driven topological phase transition.

1. Introduction
The present main challenges in nano-electronics are to reduce power consumption and to extend field effect transistor (FET) operating frequency in more intriguing frequency domains, by reducing their size while still retaining or improving the electron mobility. For these purposes, classical semiconductor technologies are coming to their limits and new materials are recently emerging as valuable alternatives to overcome these restrictions. In this perspective, topological insulators are extremely promising. Whereas their bulk is insulator, their edges are indeed composed of a set of dissipation-less states having Dirac dispersion. Therefore, because their charge carriers are massless and protected from backscattering by the intrinsic topology of the semiconductor band structure, these materials might be ideal to simultaneously achieve high electron mobility and low power consumption. Moreover, it was shown in different materials that using plasma wave effects in 2D electron channels, nanometer sized FETs can operate as efficient resonant or broadband Terahertz (THz) detectors, mixers, phase shifters and frequency multipliers at frequencies far beyond their fundamental cut-off frequency. Therefore, using plasma wave phenomena in 2D topological insulator-based FETs turns out to be an extremely promising way to take up the present-day nano-optoelectronics challenges.

In this work, we study an inverted band structure HgTe-based FET by THz photoconductivity as a function of quantizing magnetic field. We show that THz detection by nonlineairities in the FET channel allows for the observation of the magnetic field-induced quantum phase transition between non-trivial inverted band structure and trivial QH regime. These experimental results pave the way towards THz topological FETs.
2. Results and discussion
We have studied an 8.3 nm wide [013]-oriented HgTe QWs embedded in between Cd$_x$Hg$_{1-x}$Te barriers with $x = 0.77$. The sample was grown by molecular beam epitaxy (MBE) with ellipsometric control on semi-insulating GaAs [013] substrates with relaxed CdTe buffers. Its band structure was inverted. The sample has symmetric In-doped (n-type) areas around the QW layer.

Devices were fabricated using low-temperature positive electron beam lithography (EBL). The layered structure was etched using a plasma of CH$_4$:H$_2$ in a reactive ion etching (RIE) facility. The PMMA mask was patterned with EBL in shape of a rectangular 12 µm x 5 µm area, placed at the center of a 100 µm x 100 µm etched square. In order to realize a top-gate FET geometry, an 120 nm thick SiO$_2$ layer was sputtered on the sample surface and a 6 µm wide, 6 µm long gate (G) electrode was patterned at the center of the S-D distance and a 10/100 nm Ti/Au contact thermally evaporated on it.

Photoconductivity experiments were carried out at frequencies of 292 GHz and 660 GHz generated by a multiplied Schottky diode. The THz beam was modulated by a mechanical chopper at 215 Hz and guided to the sample by stainless steel pipes. The transistor was placed at the center of a superconducting coil and cooled to 4 K. We set constant 3.8 µA current in the channel. The detection signal appearing between source and drain under illumination was measured with a standard lock-in technique as a function of the magnetic field at fixed gate voltage from 0 to 750 mV.

The FET gate was leaky but allows to slightly controlling the carrier density. Figure 1 shows the electron concentration tuning with the gate bias, extracted from Shubnikov-de Haas (SdH) oscillation frequencies. Electron density varies from approximately 1.1 to 1.8 x 10$^{12}$ cm$^{-2}$. Insert (a) shows a picture of the FET used in this work. Insert (b) illustrates an example of SdH curve obtained up to 16 T at V$_g$ = 750 mV.

Figure 2 (a) shows the photoconductivity spectra as a function of magnetic field at 292 and 660 GHz. At low fields, one can see broad cyclotron resonances (CR) shifting with incident frequency. This assumption is in agreement with absorption spectra reported in Figure 2 (d) also showing CR lines roughly at the same positions. At approximately 6 T, a well pronounced peak is observed in photoconductivity data, although no trace of it is present in the transmission spectra.
One can notice however that the photon energy used in these experiments (1.2 and 2.7 meV) are few times larger than the heat sink thermal energy (0.35 meV) but smaller than the avoided crossing energy (4.3 meV), thus can hardly induce optical transition between these two bands. That is the reason why we have no other absorption lines in transmission spectra (Figure 2 (d)).

Furthermore, photoconductivity datas obtained on Van der Pauw configuration sample without gate, only show CR line and SdH-like oscillations, without any other visible resonance (Results are not shown here). Interestingly, the position of the resonance at 6 T, therefore only observed in FET configuration, is independent on incident frequency and carrier concentration, and corresponds to a critical magnetic field $B_c$ for which anticrossing of zero-mode LLs is expected.

In HgTe inverted band structure QWs, the lowest Landau level (LL) of the conduction band contains a pure heavy hole state, when the highest LL of the valence band has a more electronic character and shifts to higher energies in magnetic field. This leads to a crossing of these two peculiar LLs for a finite magnetic field depending on the QW thickness. The observation of such a LL crossing is first clear indication for the occurrence of an inverted band structure. Therefore, at this critical magnetic field, the Dirac mass parameter $M$ is tuned from negative to positive values, corresponding to a quantum phase transition between inverted, with non-trivial topology, and non-inverted band structure. The crossing of Landau levels for an inverted band structure was demonstrated experimentally by Schultz et al.\(^4\). However, it was shown in more details in\(^5\) by magneto-transmission Fourier-transform spectroscopy that instead of crossing, these zero-mode LLs are anticrossing\(^6\) because of bulk inversion asymmetry (BIA) of HgCdTe crystal. As measured experimentally and confirmed with the band structure calculations, for an 8.3 nm wide QW, the LL avoided crossing occurs at approximately 6 T.

Kane model calculation of valence and conduction bands splitted into LLs, taking into account BIA, is plotted in Figure 2 (b) as a function of magnetic field. One can see the anticrossing of the lower level of conduction band and the upper level of valence band at $B_c = 6$ T.

On the contrary of transmission spectroscopy, in the photoconductivity experiments, elementary excitations are detected by measuring the photo-induced nonlinear change of the resistance, which
monitors exactly the electronic system nonlinearities. This provides chances for exploring unique natures of excitations unable to be investigated by conventional absorption spectroscopy. Furthermore, THz photoconductivity in field effect transistors has been proven since more than 10 years in many materials, to be a powerful tool to probe the 2D electron gas nonlinearities. In usual FET, the THz electric field modulates electron density in the channel through the gate contact, and modulates carrier velocity by the source side. Thus, THz photoconductivity signal reflects a change of channel’s conductivity. Under external magnetic field, if the incident radiation frequency coincides with the cyclotron frequency, electrons are efficiently heated, inducing a significant change of conductivity, giving rise to the typical photovoltaic signal. The position of the observed cyclotron resonance peak is as expected shifting to higher values with increasing incident frequency. The observed peak shifting neither with incident frequency nor with carrier concentration is measured at around 6 T. This magnetic field value corresponds to the well-known peculiarity of the band structure in these QWs, i.e. the anticrossing of the two zero mode Landau levels. Therefore, we assume that this photoconductivity signal at approximately 6 T is linked with the magnetic field driven topological phase transition.

However, in our sample the Fermi level is much higher than the anticrossing position and the system is not in the quantum spin Hall regime. Therefore, topological edge states are not present and the observed peak cannot be attributed to helical edge states conductivity. Moreover, because the zero mode LLs are below the Fermi level and do not participate to the conduction, the electrons of the anticrossing region of the band structure shouldn’t affect directly the channel’s conductivity. Therefore, deeper theoretical work must be performed to understand how electron-electron interactions can allow the conductivity at the Fermi level to be affected by lower Landau levels.

3. Conclusion
In conclusion, we demonstrated THz photoconductivity response in inverted band structure HgTe FETs, showing a well pronounced peak at magnetic field of 6 T. Its position is independent on incident frequency and carrier concentration, and corresponds to a critical magnetic field for which particular anticrossing of zero-mode Landau levels is expected. Therefore, we assume that this resonance is related to the magnetic field-induced topological phase transition appearing in HgTe inverted band structure QWs.

Acknowledgments
This work was supported by the CNRS through LIA TeraMIR project and by the Russian Academy of Sciences, the non-profit Dynasty foundation, the Russian Foundation for Basic Research (Grants 13-02-00894, 15-02-08274), “COST action MP 1204” and by the Italian Ministry of Education, University, and Research (MIUR) through the program FIRB-Futuro in Ricerca 2010, RBFR10LULP, “Fundamental research on terahertz photonic devices”.

Reference
1 C. L. Kane, J. E. Moore 2011 Physics World 24 32
2 W. Knap, S. Rumyantsev, M.S. Vitiello, et al. 2013 Nanotechnology 24 214002
3 S. Dvoretsky, N. Mikhailov, Y. U. Sidorov, V. Shvets, S. Danilov, B. Wittman, and S. Ganichev 2010 J. Electron. Mater. 39 918
4 M. Schultz, U. Merkt, A. Sonntag, U. Rössler, R. Winkler, T. Colin, P. Helgesen, T. Skauli, and S. Lovold 1998 Phys. Rev. B 57 14772
5 M. Zholudev, F. Teppe, M. Orlita, et al. 2012 Phys. Rev. B 86 205420
6 M. S. Zholudev, F. Teppe, S. V. Morozov, M. Orlita, C. Consejo, S. Ruffenach, W. Knap, V. I. Gavrilenko, S. A. Dvoretskii, N. N. Mikhailov 2015 JETP Letters 100 790
7 S. Holland, Ch. Heyn, D. Heitmann, E. Batke, et al. 2004 Phys. Rev. Lett. 93 186804
8 M. I. Dyakonov, M. S. Shur 1993 Phys. Rev. Lett. 71 2465