Summary

Granular conductors acquired importance in the past decades because of their tunable electronic properties, which can be controlled at the nanoscale. Their importance comes from the fact that they combine the mesoscopic properties that dominate inside each grain and the collective properties of coupled nanocrystals. However, the ease of adjusting their electronic properties makes them convenient also from the fundamental point of view. In recent years the electric double layer (EDL) gating has received great attention as a powerful tool to efficiently control the surface carrier density of a wide range of different materials, reaching almost two order of magnitude higher electric fields than standard well-known field effect transistor (FET) architecture.

In this Ph.D. thesis we performed field effect measurements on different disordered thin-film systems: nominally, P-doped Barium Iron Arsenide ($BaFe_2(As,P)_2$), nano-crystalline diamond (NCD), inkjet-printed graphene and MXene, two of them being metallic systems, and the other two being carbon based semiconductors. We also performed preliminary measurements on gold and niobium nitride (NbN) with the aim of exploring the properties of ultrathin films via the ferroelectric gating technique.

Chapter 1 will introduce three different techniques to perform electric-field-effect experiments. We will introduce the solid gating technique, as a well-established tool to modulate the transport properties of low-density carrier systems; Then, the ionic gating technique, as a tool that allows to go beyond the solid-gating technique limits as far as the maximum induced charge density is concerned; Finally, the ferroelectric gating technique, which combines the ferroelectric and the piezoelectric effects to modulate the transport properties of the studied material. We will investigate the three techniques and we will resume the pros and cons for each of them.

Chapter 2 will present the results obtained on optimally-doped $BaFe_2(As,P)_2$ ultrathin films (10 nm) epitaxially grown on MgO substrates via molecular beam epitaxy. We controlled the charge density at the film surface by means of ionic gating. In order to suppress undesirable electrochemical interactions with the sample,

we designed and employed an optimized electrolyte. The resulting modulations to the resistivity were found to be compatible with an electrostatic operation of the ionic gate, with a scaling on the induced charge density consistent with an asymmetric scattering efficiency between cations and anions. At low temperatures, the T_c was suppressed both upon electron and hole doping, indicating that field-effect doping and isovalent P substitution share the same T_c maximum in the Ba-122 phase diagram. We thus demonstrated that the superconductivity (SC) is fully optimized by P substitution and any further deviation from this optimal condition is detrimental to the SC state. Additionally, we showed that field-effect doping leads to a broadening of the resistive transition. This indicates that gate-induced modulations to the SC order parameter in Ba-122 are not uniform across the entire film thickness.

Chapter 3 will show the results of ionic gating experiments on nanocrystalline boron-doped diamond (300 nm thick films) grown by Micro Wave Chemical Vapor Deposition (MW CVD). The presence of boron doping enhances the maximum induced carrier density with respect to undoped films and single crystals. By disentangling the sheet conductance of the field-induced conducting layer from that of the underlying bulk, we were able to probe the surface transport properties as a function of temperature and induced charge density. By increasing the hole density, we observed a transition from the variable-range hopping to the quantum critical regime of the insulator-to-metal transition in the surface conducting layer. However, the insulator-to-metal transition is never reached at the surface: this frustrated behaviour may be due to an increased disorder arising from a combination of surface roughness and extra scattering centres introduced by the ionic gate.

Chapter 4 will present the results obtained on graphene and MXene (specifically, Ti_3C_2) inkjet printed thin films. In the graphene-ink films, the sheet conductance reveals a dominating variable range hopping regime for 3-dimensional systems without the opening of a Coulomb gap. Electric field effect mobility measurements and magnetoresistance measurements confirm the aforementioned transport mechanism and allows to recover the hopping parametes. In MXene-ink films we observed a metallic behaviour that is closely similar to the epitaxially grown counterparts. An upturn of the resistance at low temperatures suggests the presence of incoming localization. Magnetotransport measurements reveals weak localization and the study of this allows to recover the characteristic lengths of the phenomenon.

Chapter 5 will show some preliminary results of piezoelectric gating technique on CVD gold thin films. The ferroelectric characterization of PZT was used to modulate the resistance of the gold film. With further increasing the maximum applied electric field across the PZT activates the piezoelectric polarization: this

latter has stronger effects on the gold film transport properties, covering the ferroelectric effect.
We then performed preliminary ionic-gating experiments on ultrathin CVD NbN films. Besides of hampering the superconducting properties, reducing the sample thickness has the positive effect of enhancing the capability of the SC T_c (up to 0.5 K). However, the maximum induced surface charge density we reached is $\sim 10^{14}$ e^-/cm^2, that is one order of magnitude lower than what already found in the literature for ionic-gating technique on thicker NbN films. We account this to the formation of a dead layer at the surface.
Thus, we suggest that there are perspectives of exploiting the ferroelectric gating to tune the superconductivity making these films actual superconducting transistors at low temperature. The application of ferroelectric gating technique to NbN ultrathin films is ongoing, and are not treated in this work.

Concluding, we will present future perspectives about each of the studied materials and techniques.