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Controlled formation of nanobubbles in graphene

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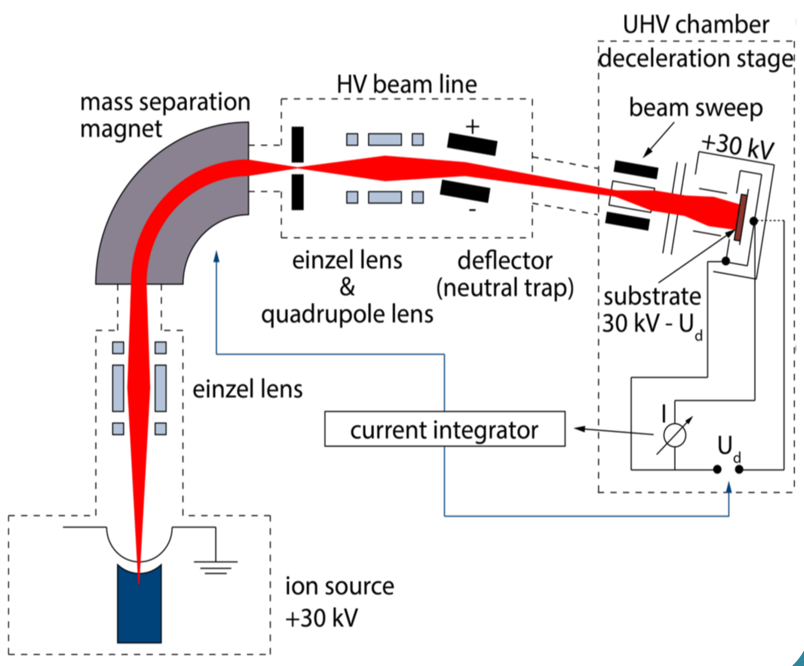
ion implantation in the ultra-low energy regime (10-100 eV): controlled intercalation with minimal damage

ultra-low energy (ULE) ion implantation

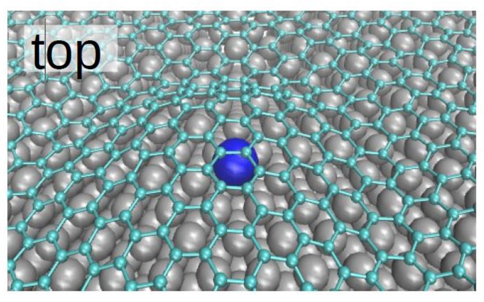
Owing to its unrivaled elasticity and strength [1], graphene is able to hold matter at extreme pressures in the form of bubbles with dimensions down to the nanometer scale [2,3]. These unique bubbles offer new opportunities to explore chemistry and physics under the extreme conditions that both graphene and the trapped matter are subject to, for example, high-pressure chemical reactions [4] and strain-induced pseudomagnetic fields [5].

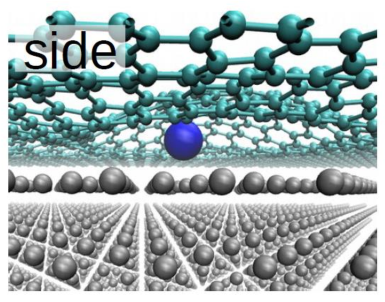
While various approaches have been explored so far, they provide limited controllability, especially on a large-wafer scale. Here we report on the controlled formation of noble gas (He, Ne, Ar) nanobubbles in graphene (on various substrates) using ultra-low energy (ULE) ion implantation [6]. ULE ion implantation allows us to precisely tune the number of implanted ions and their kinetic energy, which in turn controls the bubble formation efficiency and bubble density.

Our experimental approach is based on a wide range of characterization techniques (structural and electronic), including scanning tunneling microscopy and spectroscopy (STM/STS), synchrotron-based angle-resolved photoemission spectroscopy (ARPES), Raman spectroscopy, among others. These experimental studies are complemented by molecular dynamics (MD) calculations [3,7], which give insight into the bubble formation and stability mechanisms, and how they depend on gas species (e.g. He, Ne, Ar) and substrate (e.g. Cu and Pt). Our work is aimed to establish a framework for the controlled formation of graphene nanobubbles at wafer scale.

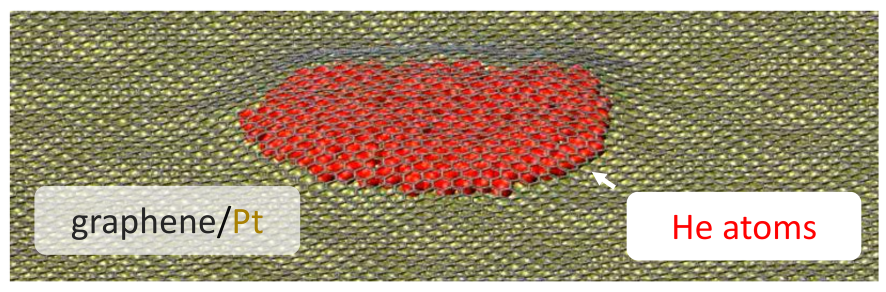


molecular dynamics simulations



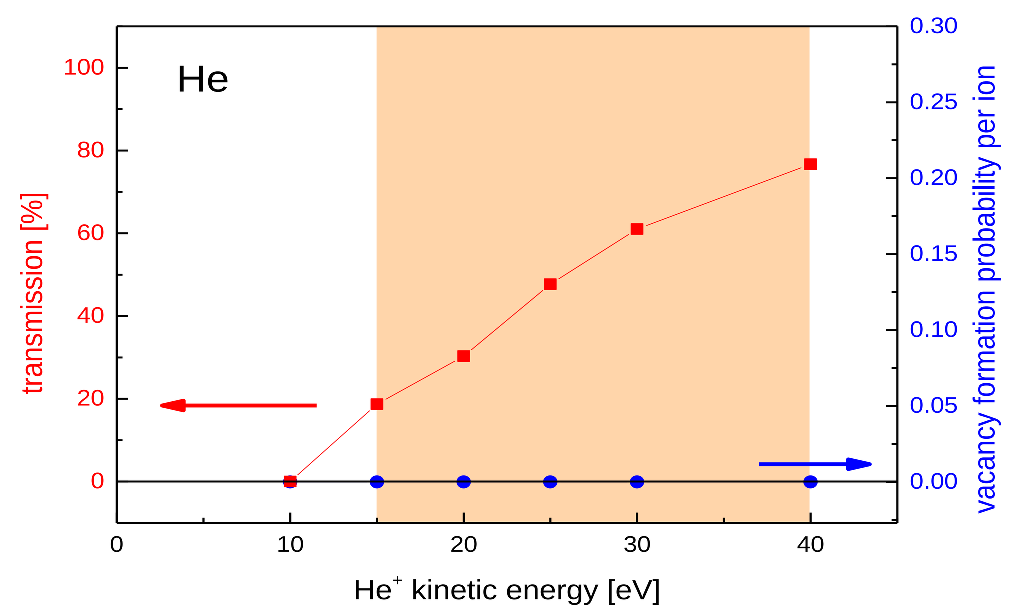


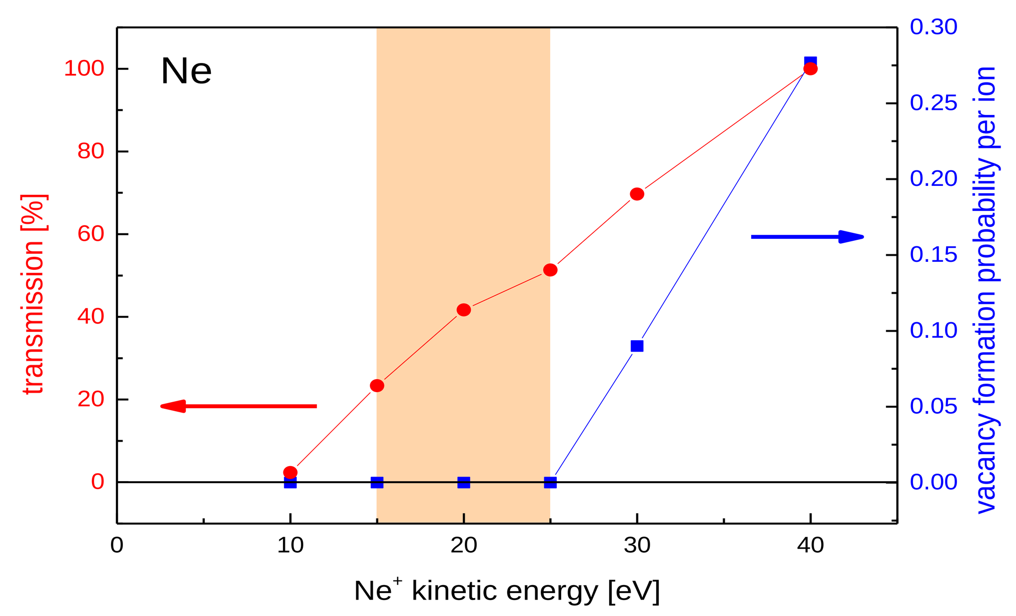
simulation of the ULE ion implantation for He, Ne and Ar ions into graphene, for ion energies between 10 and 40 eV (cf. formalism in [7])

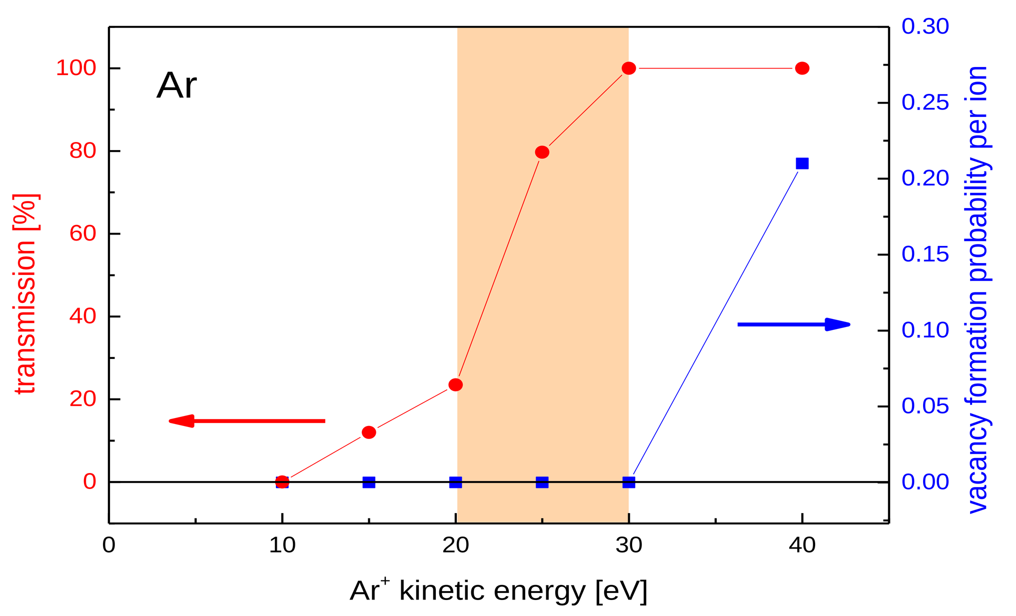


simulation of the bubble stability and morphology for He, Ne and Ar bubbles, for graphene on Pt and on Cu (cf. formalism in [3])

transmission *versus* disorder



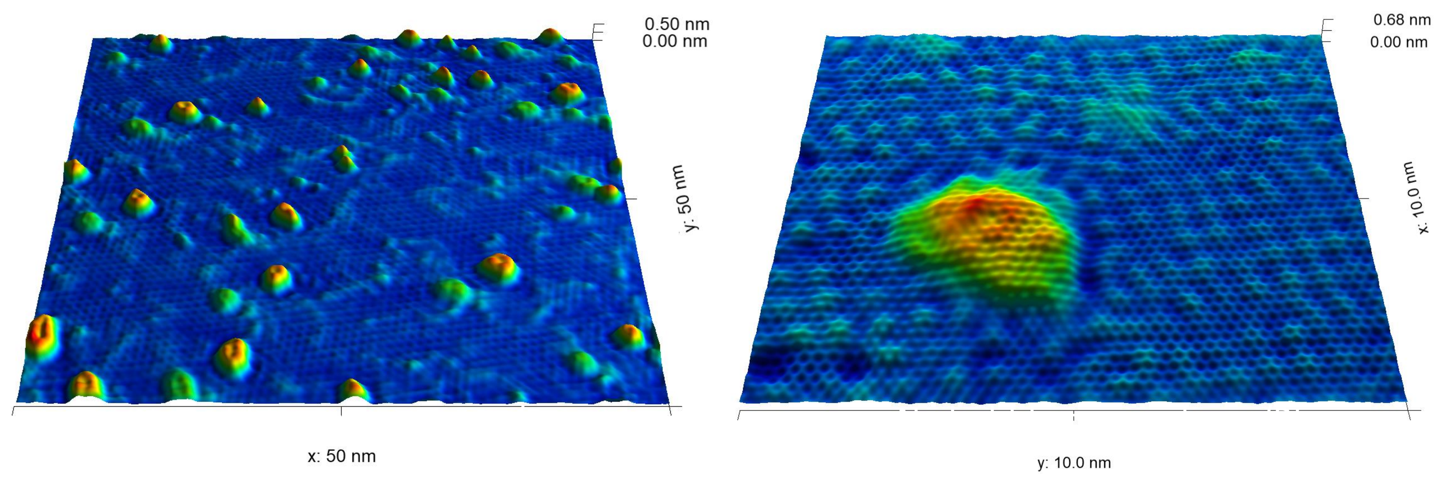




molecular dynamics simulations:
for all noble gases considered (He, Ne, Ar) there is an energy window providing high transmission (i.e. efficient intercalation) while avoiding vacancy formation

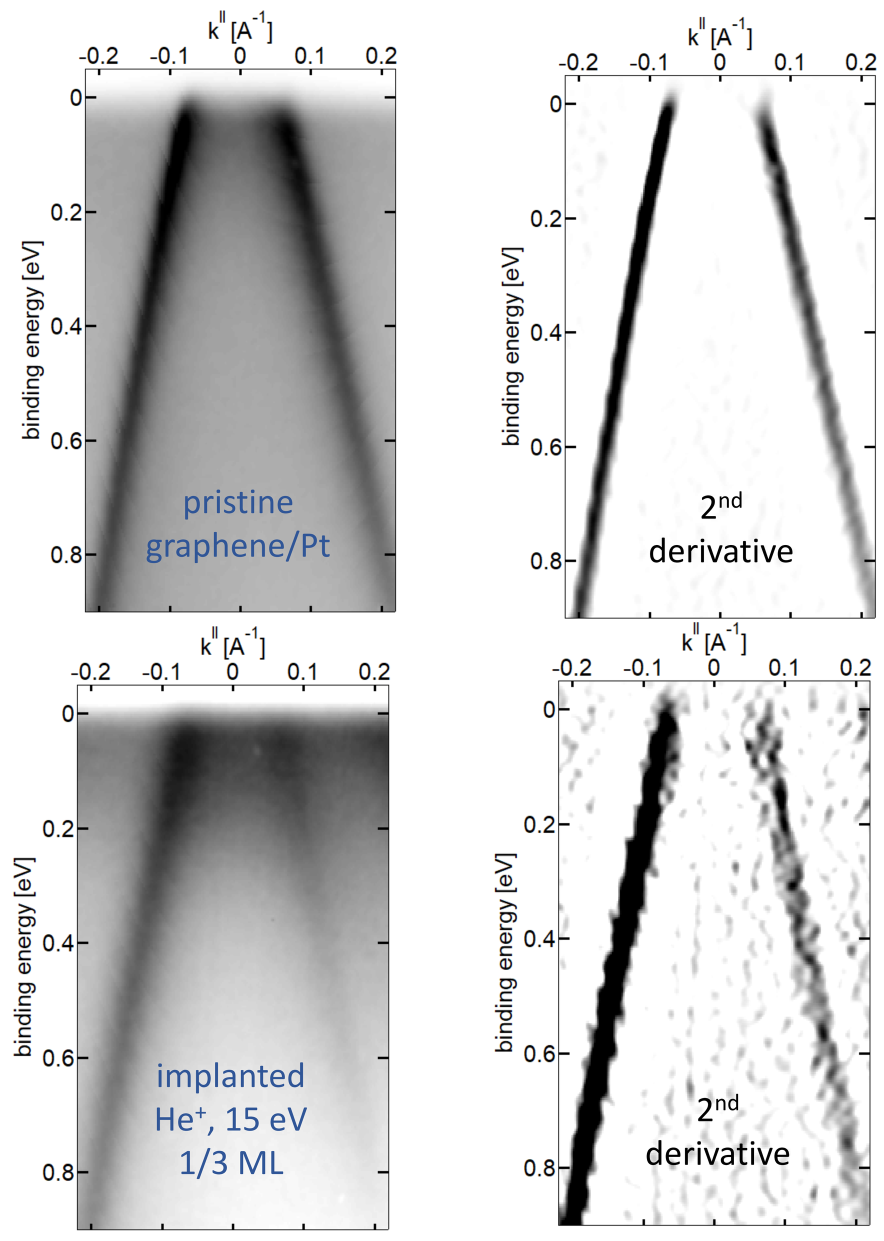
structural and electronic properties

scanning tunneling microscopy

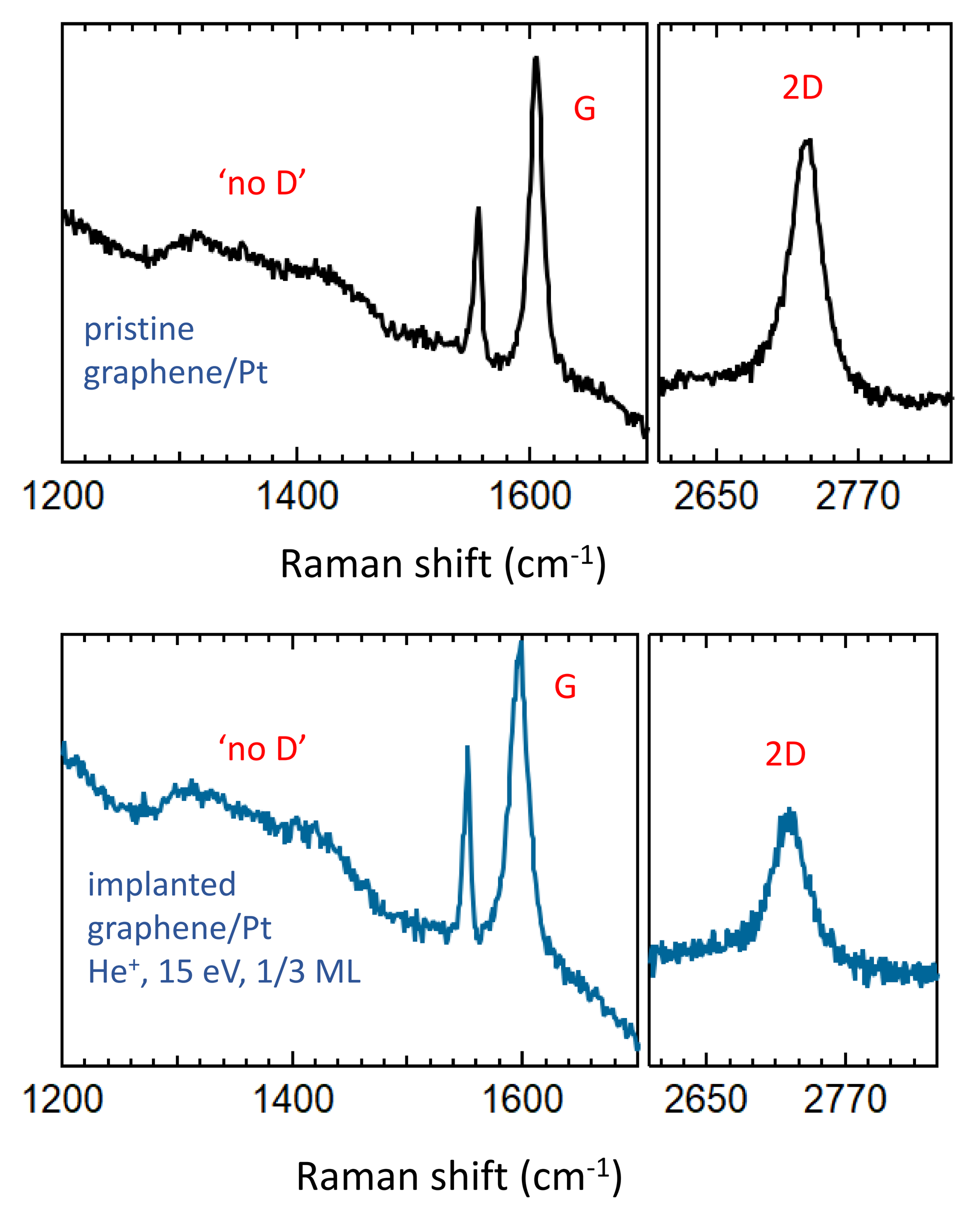


- Nanobubbles are observed for all implanted gases (He, Ne, Ar)
- Nanobubbles are stable for graphene on Pt but not for graphene on Cu
- Typical bubble size: few nm²
- Typical bubble height: few Å
- Bubble density can be tuned by implantation fluence

angle-resolved photoemission spectroscopy



Raman spectroscopy



- Disorder can be minimized and even avoided by implanting at low energy and low fluence
- Bubbles can be formed while preserving high structural order and Dirac character of graphene

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