Towards few-layer black phosphorus electronics and optoelectronics devices

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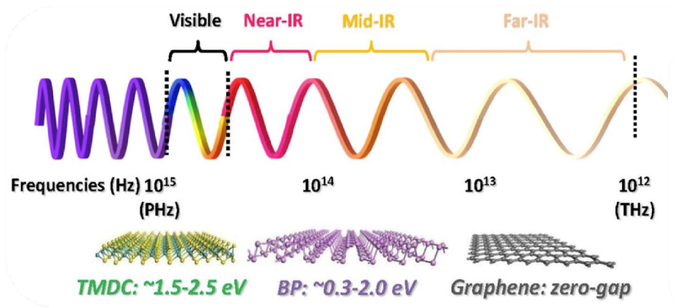
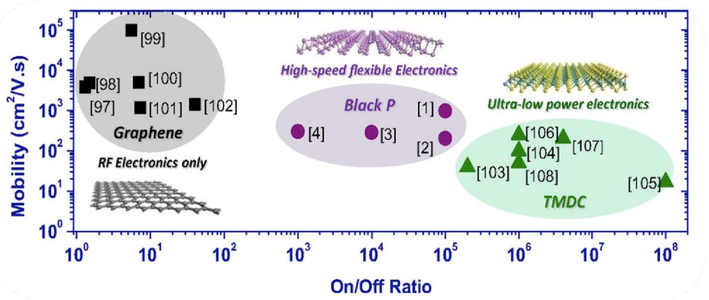
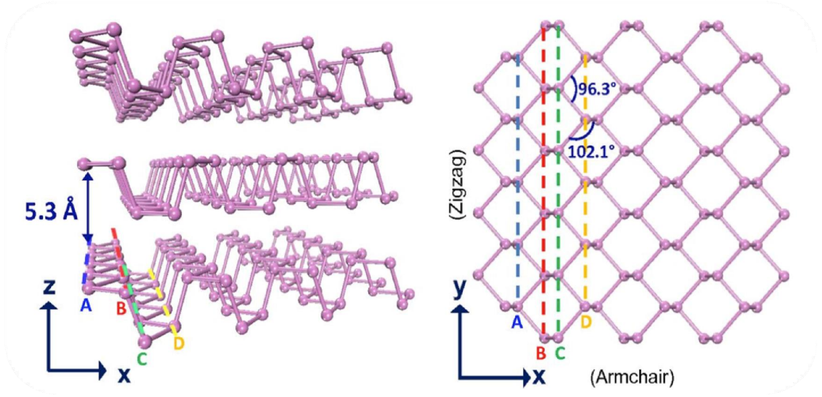
Phosphorene structure and properties





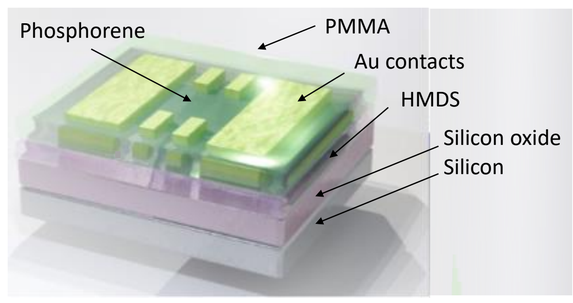


- Direct band gap (BG)
- Thickness dependent BG
- Tunability of electronic properties
- High hole mobility
- High flexibility
- Thermoelectric properties
- Strong in-plane anisotropy

[1] X. Ling et al., PNAS 112 (2015) 4523.

Phosphorene device technology

Few-layer bP holds outperforming structural properties of graphene while it overcomes the limitation of lack of a band gap. First, we aim to set-up a scalable and reproducible synthesis of mono and multilayer bP. Secondly, we move towards fabrication and characterization of bP based structures. bP is highly unstable under ambient conditions and in order to prevent oxidation, the whole processing, from exfoliation to device fabrication and characterization, must be performed under inert atmosphere or by protecting the surface with temporary passivation layers.



Exfoliated flakes on custom silicon wafers are processed with electron beam lithography (EBL) to define metal leads.

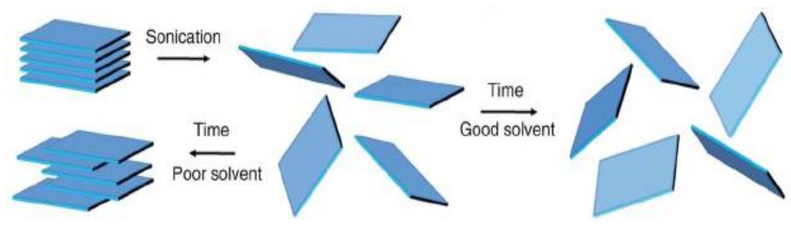
Within PHOSFUN project, bP chemical reactivity is investigated opening the perspective of devices with tunable properties.

Production routes for phosphorene layers

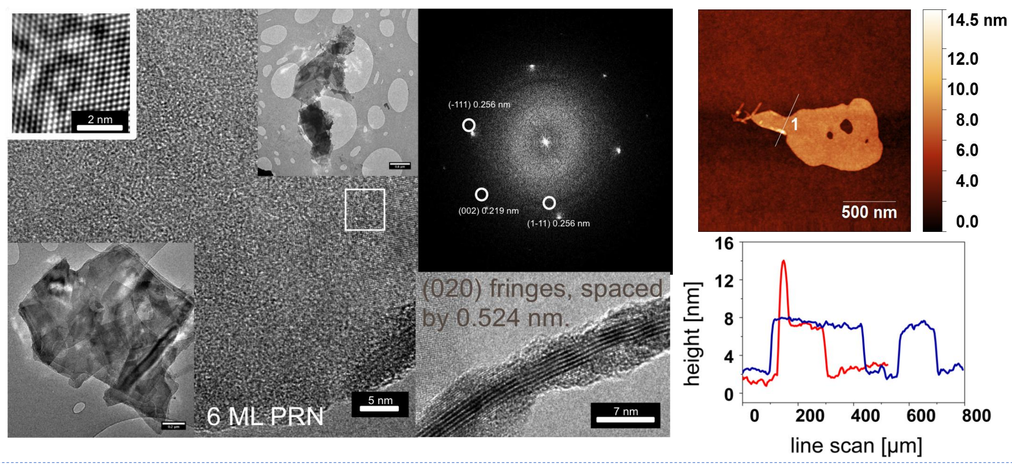
Black phosphorous (BP) crystal

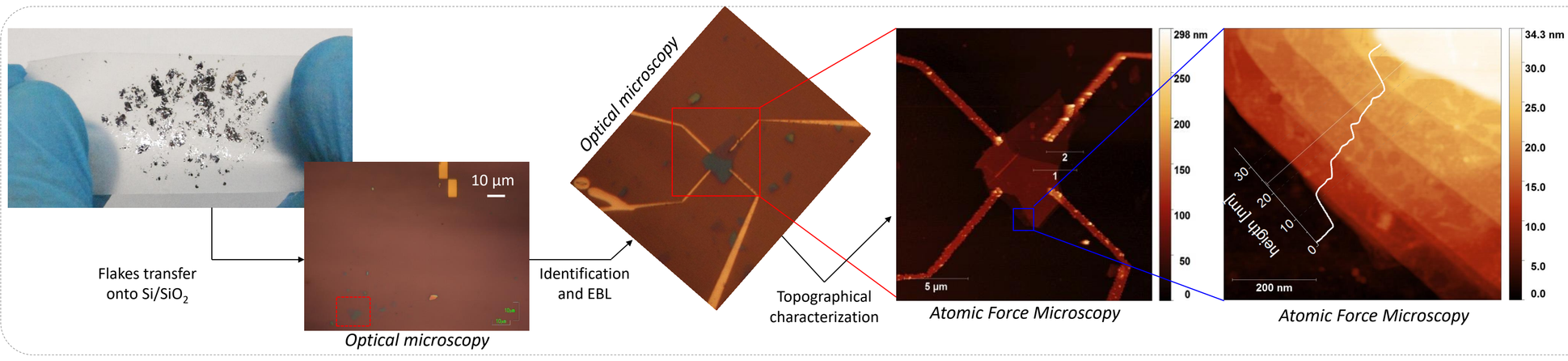
Sonication-assisted liquid exfoliation

Scotch tape exfoliation



Sonication-assisted exfoliation holds the potential for scaling up few-layer bP production. The result is a dispersion of sub-micrometer flakes, with thickness in the range of 1-10 layers. [2]

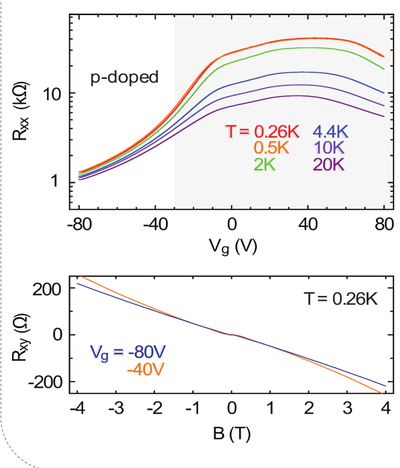




Mechanically exfoliated flakes transferred atop Si substrates have larger lateral dimensions with respect to sonication-assisted exfoliated bP. Metal leads over individual flakes are patterned using electron beam lithography (EBL). A few-layer bP based field effect transistor (FET) is fabricated.

Transport properties: study of weak localization

Low temperature (T) characterization of a bP FET of 65nm active layer thickness [3].



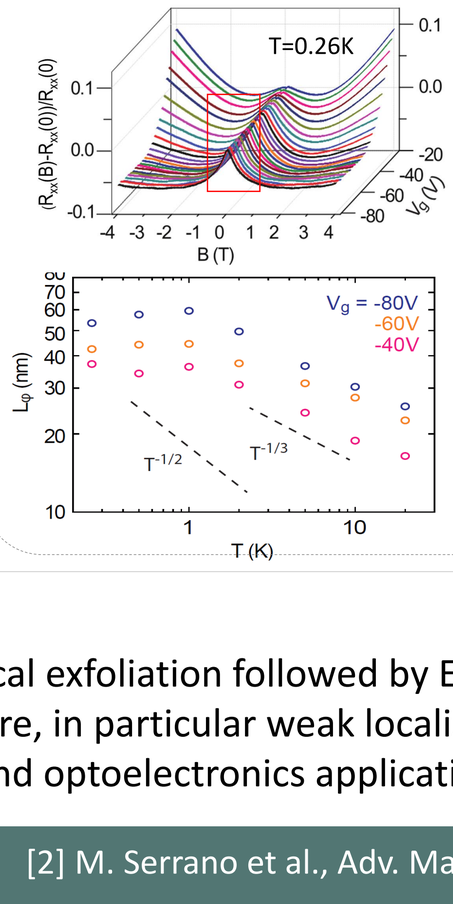
p-type semiconducting behavior for gate voltage (V_g)<-30V.

Carrier density:
$p = 10^{13}$ cm^{-2} for V_g = -30 V

Field-effect mobility μ:
300 cm^2/Vs at V_g = -70 V

Negligible T-dependence in μ for 0.26 K < T < 20 K

Weak localization is a quantum effect related to coherent scattering at low temperature.



Low temperature longitudinal magnetotransport reveals a peak at zero magnetic field: this is signature of weak localization.

Fitting the peak with Hikami-Larkin-Nagaoka model, information on inelastic scattering length (L_φ) could be extracted.

$T^{-1/2}$ behaviour for L_φ is expected in 2D materials. The anomalous $T^{-1/3}$ behavior observed is similar to the one found in quasi-1D systems. We attribute this to the puckered structure of bP which forms a strongly anisotropic medium for localization.

Therefore, the anisotropic structure of black phosphorus plays a crucial role also for quantum interference effects such as WL [3].

Conclusions and outlooks

Fabrication of few layer bP devices is obtained by mechanical exfoliation followed by EBL onto Si/SiO_2 substrates. FETs have been used to investigate fundamental properties of bP at low temperature, in particular weak localization. Furthermore, FETs can be considered the ideal platform for several fundamental studies and electronics and optoelectronics applications.

References: [1] X. Ling et al., PNAS 112 (2015) 4523 [2] M. Serrano et al., Adv. Mater. Interfaces 2015, 1500441 [3] N. Hemsworth et al, Phys. Rev B, 94, 245404, (2016)

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