Supplementary Information: Plasmons and screening in monolayer and multilayer black phosphorus

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SUPPLEMENTARY MATERIAL

Dynamical screening— The calculated real and imaginary part of $\epsilon(\mathbf{q},\omega)$ at finite ω are shown in Fig. 1, assuming $T = 300\,\text{K}$, $\eta = 10\,\text{meV}$ and an electron density $n = 1\times 10^{12}\,\text{cm}^{-2}$. The most significant contribution to $\Re[\epsilon(\mathbf{q},\omega)]$ occurs when $\mathbf{q}$ and ω coincide with the single particle (SP) phase space whose boundaries are given by, $\hbar\omega^{\pm}_{SP}(\mathbf{q}) = E(\pm\mathbf{k}_F + \mathbf{q}) - E(\mathbf{k}_F)$. On the other hand, finite losses as modeled by the phenomenological parameter η, are reflected in contributions to $\Im[\epsilon(\mathbf{q},\omega)]$ in regions of phase space in proximity to $\hbar\omega^{+}_{SP}(\mathbf{q})$. In general, $\epsilon(\mathbf{q},\omega)$ in BP exhibits strong directional dependence with $\mathbf{q}$. Anisotropic dynamic screening might have important implications to carrier relaxation processes such as scattering with polar optical phonons.

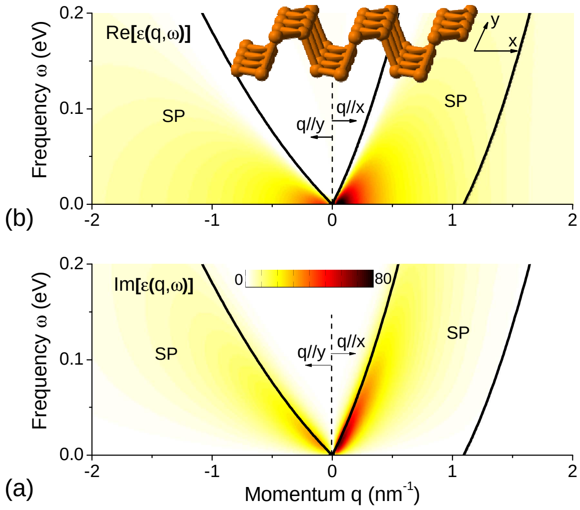

FIG. 1: **(a-b)** Intensity plot of the real (top) and imaginary (bottom) part of the dielectric function $\epsilon(q,\omega)$ of monolayer BP for wave-vector $\mathbf{q}$ directed along the two crystal axes {x,y} as defined in the inset. Calculations assumed $T = 300\,\text{K}$, $\eta = 10\,\text{meV}$ and electron density $n = 1\times 10^{13}\,\text{cm}^{-2}$.

Drude weights— In Fig. 2, we show the general trend of increasing Drude weight (within the effective mass model described in the main paper) with film's thickness, primarily due to the decreasing effective masses. We also quantify the effect of non-parabolicity on the Drude weight. Here, the Drude weight is extracted from the numerically computed conductivity at long wavelength limit, which includes the full band dispersion. The deviation between the two models implies strong non-parabolicity effect, due to interband coupling, which is particularly strong when the energy gap of the BP film is $\ll \gamma^2/\eta_{c,v}$. In other words, non-parabolicity effect is more prominent for thicker films.

Interlayer screening for p-doped samples— Here we show the results for hole doped samples in Fig. 3. Since BP is electron-hole asymmetric, our results differ depending on the type of doping. We find that the screening is less effective for n-doped samples than for p-doped samples. This is a consequence of the electron-hole asymmetry of the

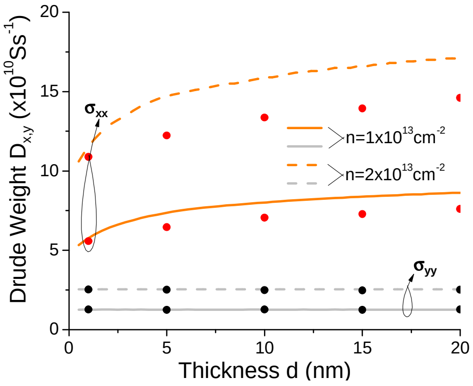

FIG. 2: Drude weights as function of layer thickness, computed with and without band non-parabolicity effect.

system, which presents a higher dispersion of the bands along z-direction for the conduction band as compared to the valence band.

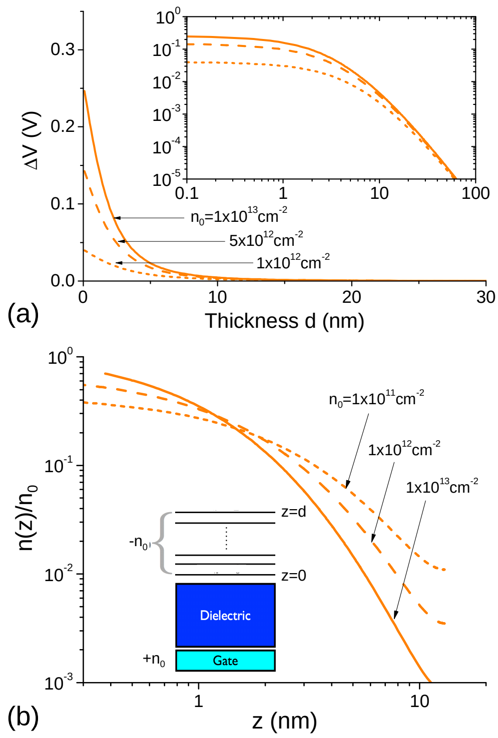

FIG. 3: **(a)** Potential difference $\Delta V(d)$ as a function of the thickness for an electron doped sample, obtained from the Thomas-Fermi model discussed in the text. We show the results for different carrier concentrations n_0. The insets show the same results in a logarithmic scale. **(b)** Normalized surface-charge distribution $n(z)$ induced in a 13 nm thick sample for different gate carrier densities n_0 as stated. The inset shows an sketch of the microscopic model is shown.

Experimentally measured on/off ratio of multilayers BP transistor— Here we show the experimentally measured on/off ratio of multilayers BP transistor in Fig. 4. For an on-state carrier density around $6 \times 10^{12}\,\mathrm{cm}^{-2}$, the on/off current ratios of the field-effect transistors reduce sharply from around $I_{on}/I_{off} = 5 \times 10^4$ for 5 nm thick BP channels to around only $I_{on}/I_{off} = 100$ for 10 nm thick BP channels.

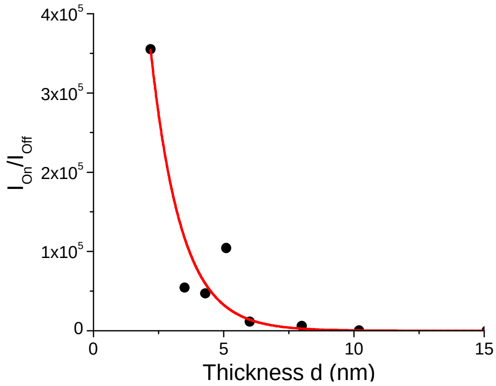

FIG. 4: Experimentally measured on/off ratio of multilayers BP transistor, for an on-state carrier density around $6 \times 10^{12}\,\mathrm{cm}^{-2}$, and at a given off-state current. See also Ref. [1].

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[1] F. Xia, H. Wang, and Y. Jia, arXiv:1402.0270 (2014).