Acoustically-driven surface and hyperbolic plasmon-phonon polaritons in graphene/h-BN heterostructures on piezoelectric substrates

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Abstract
Surface plasmon polaritons in graphene couple strongly to surface phonons in polar substrates leading to hybridized surface plasmon-phonon polaritons (SPPPs). We demonstrate that a surface acoustic wave (SAW) can be used to launch propagating SPPPs in graphene/h-BN heterostructures on a piezoelectric substrate like AlN, where the SAW-induced surface modulation acts as a dynamic diffraction grating. The efficiency of the light coupling is greatly enhanced by the introduction of the h-BN film as compared to the bare graphene/AlN system. The h-BN interlayer not only significantly changes the dispersion of the SPPPs but also enhances their lifetime. The strengthening of the SPPPs is shown to be related to both the higher carrier mobility induced in graphene and the coupling with h-BN and AlN surface phonons. In addition to surface phonons, hyperbolic phonons polaritons (HPPs) appear in the case of multilayer h-BN films leading to hybridized hyperbolic plasmon-phonon polaritons (HPPPs) that are also mediated by the SAW. These results pave the way for engineering SAW-based graphene/h-BN plasmonic devices and metamaterials covering the mid-IR to THz range.

Keywords: graphene, surface plasmon phonon polariton, surface acoustic waves, h-BN, hyperbolic polaritons

(Some figures may appear in colour only in the online journal)

1. Introduction
Surface plasmon polaritons (SPPs) are electromagnetic waves confined to the interface between two materials and accompanied by collective oscillations of surface charges. One of the most intriguing properties of SPPs is that their momentum is larger than that corresponding to free photons of the same frequency [1]. As a consequence, SPPs are bound modes whose fields decay exponentially away from the interface, exhibiting deep subwavelength confinement which results in strong light–matter interaction [2, 3]. Thus, SPPs in metals have attracted a strong interest over the last few decades for manipulating light and light–matter interactions at scales well beyond the diffraction limit [4] and have laid the foundation...
of a whole new range of fields including SPP-based nanophotonic devices [5, 6], metamaterials [7], metasurfaces [8], and quantum plasmonics [9]. However, the lifetime of SPPs in metals is extremely short when the light is confined to deep subwavelength scales and their properties cannot be modulated in situ [10, 11]. In the case of doped graphene, SPPs can be confined to extreme subwavelength scales while preserving a long lifetime [10]. The carriers in graphene interact strongly with the surface optical (SO) phonons of polar substrates via the long-range Fröhlich coupling leading to hybridized surface plasmon-phonon polaritons (SPPPPs) [12, 13]. Moreover, unlike metals, the SPP (or SPPP) wavelength in graphene can be tuned in situ through the modulation of the carrier density by electrostatic gating, thus providing a versatile plasmonic platform covering the mid-IR to THz range [14–16]. Hence, graphene plasmonics are being investigated for a large number of applications including 2D transformation optics [17], optical signal processing [17, 18], single photon nonlinear optics [19], biosensing [20], and integrated optics [21].

In order to excite a SPP (or SPPP) in graphene, a large momentum mismatch has to be overcome. Momentum can be gained either using near-field techniques [22–24], frequency mixing [25], or diffraction at nanostructures using far-field radiation, where the nanostructures can be made by patterning the graphene film itself [12, 26, 27] or the substrate where the graphene layer is transferred to [28, 29]. Surface acoustic waves (SAWs) have been shown to provide a suitable mechanism to launch propagating SPPPPs in unpatterned graphene using simple far-field excitation [30]. An interdigital transducer (IDT) on a piezoelectric film is used to launch the SAW across the graphene sheet creating a tunable optical grating without the need of any patterning in either the graphene layer or the substrate, thus eliminating edge scattering and fragility issues. In addition to these advantages, the use of IDTs enables the fabrication of graphene plasmonic devices by the microelectronics industry, as compared to other schemes using an external mechanical vibrator [31]. Moreover, the use of IDTs permits to efficiently control the SPPP both temporally and spatially. Thus, the propagating SPPP can be switched electrically via the high-frequency signal at the IDT and its wavefront can be shaped by tailoring the IDT design. For example, curved IDTs creating interfering SAWs could be used for focusing the SPPP.

In this paper, we provide a complete simulation study of graphene SPPP excited by means of a SAW in graphene/h-BN/AlN heterostructures with varying h-BN film thickness. The atomically flat surface without dangling bonds of h-BN is known to provide the largest carrier mobility in graphene as compared to any other insulating substrate [32–34]. We show that the introduction of an h-BN film between the graphene and the AlN substrate not only enhances the SPPP lifetime, but also significantly changes the hybridized SPPP dispersion, as compared to the previously studied graphene/AIN system [30]. The lifetime enhancement provided by the h-BN interlayer is shown to be related to both the higher carrier mobility in graphene and the larger lifetime of the surface phonons as compared to the AlN substrate. In addition, hyperbolic phonons polaritons (HPPs) appear in the case of multilayer h-BN films, presenting high confinement ratios and quality factors [35]. HPPs in multilayer h-BN are difficult to modulate but when coupled with the graphene carriers, leading to hybridized hyperbolic plasmon-phonon polaritons (HPPPs), they can be modulated by changing the Fermi energy of graphene. The HPPPs in graphene/h-BN have been demonstrated to have minimal ohmic losses and propagation lengths two times greater than that of HPPs in bare h-BN [24, 36]. We demonstrate that a SAW can also be used to couple light into HPPPs in the graphene/h-BN/AlN systems.

2. Optical properties of graphene, h-BN, and AlN

The frequency-dependent conductivity of graphene in the local limit (k → 0) and for ω ≫ τ−1 is can be calculated using the Kubo formula [37] as

\[ \sigma(\omega) = \frac{e^2}{i\hbar} \left( \frac{1}{\omega + i\tau} \right)^2 \int_0^\infty \frac{E(\omega + i\tau)}{(\omega + i\tau)^2 - 4(\hbar/\tau^2)^2} dE \]

where \( F(E) = (\exp \{ -(E - \mu_c)/k_B T \} + 1)^{-1} \) is the Fermi-Dirac distribution, \( \mu_c \) is the chemical potential and \( \tau_e \) is the electron relaxation time. \( \tau_e \) is related to the mobility, \( \mu \), and the Fermi energy, \( E_F \), by \( \tau_e = \mu e v_F^{-2} \) where \( v_F \) is the Fermi velocity of 10^6 m/s. The first and second terms in equation (1) represent the contributions of the intraband (\( h\omega < 2E_F \)) and interband (\( h\omega \geq 2E_F \)) transitions, respectively, as shown in figure 1(a).

h-BN is an anisotropic van der Waals crystal with two IR active phonon modes: the in-plane (∥) A_{2u} phonon modes, with frequencies \( \omega_{TO} = 0.096 \) eV and \( \omega_{LO} = 0.102 \) eV, and the out-of-plane (⊥) E_{1u} phonon modes, with frequencies \( \omega_{TO} = 0.169 \) eV and \( \omega_{LO} = 0.199 \) eV [36]. The frequency-dependent relative permittivity of h-BN is given by [36]

\[ \epsilon_m(\omega) = \epsilon_{\infty,m} \frac{(\omega^2_{TO,m} - \omega^2_{LO,m})}{(\omega^2_{TO,m} - \gamma m\omega - \omega^2)} \]

where \( m = \parallel, \perp; \epsilon_{\infty,\parallel} = 2.95 \) and \( \epsilon_{\infty,\perp} = 4.87 \) are the high-frequency dielectric constants; and \( \gamma \parallel = 0.49 \) meV and \( \gamma \perp = 0.62 \) meV are the damping frequencies [36]. The permittivity of h-BN becomes negative in the frequency range between the TO and LO phonons (\( \omega_{TO,m} < \omega < \omega_{LO,m} \)), leading to two reststrahlen bands. The opposite sign in the in-plane and out-of-plane components within these bands makes h-BN a hyperbolic material. The lower band presents type-I hyperbolicity (Re(\( \epsilon_\parallel \)) < 0, Re(\( \epsilon_\perp \)) > 0), whereas the upper band has type-II hyperbolicity (Re(\( \epsilon_\parallel \)) > 0, Re(\( \epsilon_\perp \)) < 0), as shown in figure 1(b).

AIN is only slightly anisotropic [38] as compared to h-BN. Thus, for simplicity, we assume an isotropic behaviour with a unique reststrahlen band located between \( \omega_{TO} = 0.083 \) eV and \( \omega_{LO} = 0.111 \) eV, as shown in figure 1(b). The frequency-dependent relative permittivity of AIN is given by
\[ \epsilon(\omega) = \epsilon_\infty + (\epsilon_0 - \epsilon_\infty) \left( \frac{\omega_{\text{TO}}^2}{\omega_{\text{TO}}^2 - \gamma^2} \right), \]  

(3)

where \( \epsilon_0 = 7.37 \) and \( \epsilon_\infty = 3.93 \) are the static and high-frequency dielectric constants, respectively, and \( \gamma = 0.64 \) meV is the damping frequency \([39]\).

### 3. Dispersion of SPPPs and HPPPs in graphene/h-BN/AlN systems

The carriers in graphene couple to the long-range electric field induced by optically active phonons in the surrounding materials. Both h-BN and AlN are polar materials, so that their SO phonons strongly couple to graphene carriers. Thus, graphene carriers can interact by exchange of SO phonons leading to a potential given by \([34]\)

\[
V_c(k) = \frac{\epsilon^2}{k \epsilon_{\text{vac}}} \left( \epsilon_{\infty, hBN} \epsilon_{\infty, hBN} \right)^{1/2} + \epsilon_{\text{AIN}} \tanh \left[ kd \left( \frac{\epsilon_{\infty, hBN}}{\epsilon_{\infty, hBN}} \right)^{1/2} \right] \tanh \left[ kd \left( \frac{\epsilon_{\infty, hBN}}{\epsilon_{\infty, hBN}} \right)^{1/2} \right].
\]

(5)

(\( \epsilon_{\text{vac}} = \frac{e^2}{4 \pi \epsilon_0 c} \) the permittivity of vacuum and \( d \) is the thickness of h-BN and phonon exchange, \( V_{\text{SO}}(k, \omega) \)).

Within the random phase approximation (RPA), the total effective carrier interaction \( V_{\text{eff}}(k, \omega) \) is given by \([12, 13]\)

\[
V_{\text{eff}}(k, \omega) = \frac{V_c(k)}{\epsilon_{\text{RPA}}} = \frac{V_c(k) + V_{\text{SO}}(k, \omega)}{1 - (V_c(k) + V_{\text{SO}}(k, \omega)) \prod_{\rho\rho} \left( k, \omega \right)},
\]

(6)

where \( \epsilon_{\text{RPA}} \) is the total dielectric screening function and \( \prod_{\rho\rho} \left( k, \omega \right) \) is the non-interacting part (i.e. the pair-bubble...
diagram) of the charge-charge correlation function (2D polarizability). The latter is given by the modified Lindhard function [43, 44]

\[
\prod \rho \rho (k, \omega) = \frac{-g_s g_v}{4 \pi^2} \int d^2q \sum_{ss'} f_{ss'} (q, q + k) \times \frac{F(E_s(q)) - F(E_{s'}((q + k))}{E_s(q) - E_{s'}((q + k)) + i\omega + i\hbar \tau_0},
\]

(7)

where \(g_s = g_v = 2\) are the spin and valley degeneracies, respectively, \(s, s' = \pm 1\) denote the band indices, \(E_{s'}(q) = \pm \hbar v_F q - \mu_s\) are the eigenenergies, \(F(E_s(q)) = [\exp \{E_s(q)/k_B T\} + 1]^{-1}\) is the Fermi-Dirac distribution, and \(f_{ss'} (q, q + k)\) is the band overlap of the wavefunction. The latter term includes the characteristic difference between the polarizability of the Dirac (massless) electron gas in graphene and a Fermi (massive) 2D electron gas in a semiconductor system. It is given by the expression [43, 44]

\[
f_{ss'}(q, q + k) = \frac{1}{2} \left( 1 + ss' \frac{q + k \cos \theta}{|q + k|} \right),
\]

(8)

where \(\theta\) is the angle between \(q\) and \(q + k\). In the limit \(\omega > v_F k\) and \(E_F \gg \min (\hbar \omega, T)\), \(\prod_{\rho \rho} (k, \omega)\) can be approximated to [26]

\[
\prod_{\rho \rho} (k, \omega) \approx \frac{E_F k^2}{\pi \hbar^2 (\omega + i\tau_0)^2}.
\]

(9)

The electron energy loss function \(L(k, \omega) = -\text{Im} \{1/\epsilon_{RPA}(k, \omega)\}\) characterizes the spectral density of collective charge excitations. The SPPP dispersion can be obtained by solving the equation \(\epsilon_{RPA}(k, \omega) = 0\), corresponding to the poles of

\[Figure\ 2.\ \text{SPPP\ dispersion\ for\ (a)\ graphene/AlN\ and\ (c)\ graphene/h-BN/AlN\ with\ an\ h-BN\ film\ thickness\ }d = 1\ \text{nm.\ Parameters\ are } E_F = 0.4\ \text{eV\ for\ both\ structures\ and } \mu = 5000\ \text{and}\ 10000\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}\ \text{for\ graphene/AlN\ and\ graphene/h-BN/AlN,\ respectively.\ Dashed\ horizontal\ lines\ correspond\ to\ the\ phonon\ frequencies\ of\ AlN\ and\ h-BN,\ whereas\ the\ dashed\ vertical\ lines\ indicate\ SAW\ wavelengths\ }\lambda_{SAW}\ \text{of}\ 0.25\ \text{and}\ 1\ \text{\mu m}.\ (b),\ (d)\ lifetime\ of\ the\ SPPP.\]
The graphene/AlN system permits to achieve deep sub-wavelength confinement of the radiation. With the addition of h-BN, a broader range of energy for confinement can be covered. Figure 3 presents the confinement ratio \( \lambda_{\text{air}}/\lambda_{\text{SPPP}} \) as a function of the incident light wavelength \( \lambda_{\text{air}} \). The mid-IR to THZ range can be covered with confinement ratios of up to two orders of magnitude.

The dispersion of the graphene/h-BN/AlN system strongly depends on the thickness \( d \) of the h-BN interlayer, as shown in Figure 4. As \( d \) increases, SPPP\(_1\) and SPPP\(_4\) shift towards higher energies, whereas SPPP\(_3\) shifts towards lower energies, and SPPP\(_2\) does not vary substantially, as shown in Figures 2(c), 4(a) and (b) for \( d = 1, 5, \) and 10 nm, respectively. For \( d = 50 \) and 70 nm, see Figures 4(c) and (d) respectively. HPPPs [24, 40] appear within the h-BN reststrahlen bands as a result of the natural hyperbolicity of h-BN. These HPPPs appear also in the dispersion of the thinner multilayer h-BN films considered here but at higher \( k \) values than those depicted in Figures 2(c), 4(a) and (b). In general, the thicker the h-BN interlayer, the stronger its influence on the dispersion curve of the graphene/h-BN/AlN system, with the HPPP, appearing at lower \( k \) values, and the weaker the influence of the AlN substrate. Also, increasing the thickness of the h-BN interlayer from 50 to 70 nm, a transition from SPPP\(_3\) to SPPP\(_2\) is observed, as shown in Figures 4(c) and (d). This crossover is also attributed to the fact that, increasing the h-BN thickness the influence of the AlN substrate weakens, while that of the h-BN interlayer strengthens. In summary, by increasing the h-BN thickness the dispersion of the three-layer system (graphene/h-BN/AlN) seems to move gradually towards an effective two-layer system (graphene/h-BN).

SPPPs and HPPPs lead to enhanced absorption of the incident light. The transmittance and reflectance of the graphene/h-BN/AlN system can be calculated from the Fresnel reflection and transmission coefficients by means of the transfer matrix method [45]. Hence, the transfer matrix is given by \( M = B_{01}P_{12} \), where \( B_{01} \) and \( B_{12} \) are the transfer matrices for the air/h-BN and h-BN/AlN interfaces, respectively, and \( P \) is the propagation matrix. These matrices are given by the expressions

\[
B_{01} = \begin{pmatrix}
1 + \sigma(\omega)/Z_1 + Z_0/Z_1 & 1 - \sigma(\omega)/Z_1 - Z_0/Z_1 \\
1 + \sigma(\omega)/Z_1 - Z_0/Z_1 & 1 - \sigma(\omega)/Z_1 + Z_0/Z_1
\end{pmatrix} 
\]

(10.1)

\[
B_{12} = \begin{pmatrix}
1 + Z_1/Z_2 & -Z_1/Z_2 \\
-Z_1/Z_2 & 1 + Z_1/Z_2
\end{pmatrix}
\]

(10.2)

\[
P = \begin{pmatrix}
e^{-ik_dz} & 0 \\
0 & e^{ik_dz}
\end{pmatrix}.
\]

(10.3)

where \( j = 0, 1, 2 \) for air, h-BN, and AlN respectively, \( Z_j = \sqrt{\epsilon_j/\epsilon_j} \) is the impedance of \( j \)th material, where \( \epsilon_j = \left[\epsilon_j^2 (\omega/c)^2 - k_j^2/\epsilon_j^2\right]^{-1/2} \), and \( \sigma(\omega) \) is the conductivity of graphene defined in equation (1).

\[
L(k, \omega). \text{ The lifetime of the SPPP, } \tau_p \text{ can be calculated by solving the equation } \epsilon_{\text{PPA}}(k, \omega_p - ir_p^{-1}) = 0.
\]

Figures 2(a) and (c) depict the SPPP dispersion for the graphene/AlN and graphene/h-BN/AlN systems, respectively, where the latter has a 1 nm-thick h-BN interlayer. The graphene mobility has been considered to be enhanced by the h-BN film from \( \mu = 5000 \) to 10,000 cm\(^2\) V\(^{-1}\) s\(^{-1}\), whereas \( E_F = 0.4 \text{ eV} \) has been set for both cases. The dispersion of the graphene/h-BN/AlN system presents a larger number of SPPPs than those depicted in Figures (2), 4(a) and (b). In general, the thicker the h-BN interlayer, the stronger its influence on the dispersion curve of the graphene/h-BN/AlN system, with the HPPP, appearing at lower \( k \) values, and the weaker the influence of the AlN substrate. Also, increasing the thickness of the h-BN interlayer from 50 to 70 nm, a transition from SPPP\(_3\) to SPPP\(_2\) is observed, as shown in Figures 4(c) and (d). This crossover is also attributed to the fact that, increasing the h-BN thickness the influence of the AlN substrate weakens, while that of the h-BN interlayer strengthens. In summary, by increasing the h-BN thickness the dispersion of the three-layer system (graphene/h-BN/AlN) seems to move gradually towards an effective two-layer system (graphene/h-BN).

SPPPs and HPPPs lead to enhanced absorption of the incident light. The transmittance and reflectance of the graphene/h-BN/AlN system can be calculated from the Fresnel reflection and transmission coefficients by means of the transfer matrix method [45]. Hence, the transfer matrix is given by \( M = B_{01}P_{12} \), where \( B_{01} \) and \( B_{12} \) are the transfer matrices for the air/h-BN and h-BN/AlN interfaces, respectively, and \( P \) is the propagation matrix. These matrices are given by the expressions

\[
B_{01} = \begin{pmatrix}
1 + \sigma(\omega)/Z_1 + Z_0/Z_1 & 1 - \sigma(\omega)/Z_1 - Z_0/Z_1 \\
1 + \sigma(\omega)/Z_1 - Z_0/Z_1 & 1 - \sigma(\omega)/Z_1 + Z_0/Z_1
\end{pmatrix} 
\]

(10.1)

\[
B_{12} = \begin{pmatrix}
1 + Z_1/Z_2 & -Z_1/Z_2 \\
-Z_1/Z_2 & 1 + Z_1/Z_2
\end{pmatrix}
\]

(10.2)

\[
P = \begin{pmatrix}
e^{-ik_dz} & 0 \\
0 & e^{ik_dz}
\end{pmatrix}.
\]

(10.3)

where \( j = 0, 1, 2 \) for air, h-BN, and AlN respectively, \( Z_j = \sqrt{\epsilon_j/\epsilon_j} \) is the impedance of \( j \)th material, where \( \epsilon_j = \left[\epsilon_j^2 (\omega/c)^2 - k_j^2/\epsilon_j^2\right]^{-1/2} \), and \( \sigma(\omega) \) is the conductivity of graphene defined in equation (1).
For TM-polarized light, the Fresnel reflection \(r_{TM}\) and transmission \(t_{TM}\) coefficients are given in terms of elements of the transfer matrix \(M\) as \(r_{TM} = M_{21}/M_{11}\) and \(t_{TM} = 1/M_{11}\). The absorption of the light is given by \(\text{Im}[r_{TM}]\), which is interpreted as the contour plot of electron energy loss function in figures 2 and 4.

4. SAW-mediated SPPPs and HPPPs

The wave vector mismatch between the light and the SPPPs and HPPPs in the graphene/h-BN/AlN system can be overcome using an IDT on the surface of the AlN substrate to launch a SAW propagating across the graphene/h-BN heterostructure. The SAW produces a sinusoidal deformation of the surface creating a virtual dynamic diffraction grating that provides the extra wave vector required for the light to couple into the SPPPs \[34\] and HPPPs. Thus, in the presence of a SAW of wavelength \(\lambda_{SAW}\) and amplitude \(\delta\), the transmission of TM-polarized light is reduced as the SAW-induced diffraction grating scatters the incident light with wave vector \((k_{\parallel}, k_z)\) into the various diffraction orders \((k_{\parallel m}, k_{zm})\) with

\[
k_{\parallel m} = (\omega/c) \sin \theta + m2\pi/\lambda_{SAW}. \tag{11}
\]
Figure 5 shows the evolution of the strength (expressed as the maximum value of the peak in the $\Delta T^{TM}$ spectra) of the different SPPP and HPPP dispersion in the graphene/h-BN/AlN system provided by the thickness of the h-BN interlayer, graphene presents an intrinsic degree of tunability by means of the modulation of its carrier density $n$, or $E_F = \hbar v_F/\sqrt{m_\ast}$, through electrostatic gating. All SPPP$_1$ and HPPP$_1$ blue shift as the $E_F$ increases, as expected from the hybridization with a higher energy graphene plasmon. However, the intensity of a particular SPPP$_i$ or HPPP$_i$ is especially enhanced at certain h-BN film thickness and $E_F$ combinations. Therefore, a detailed study of the dispersion of the graphene/h-BN/AlN system, both in terms of h-BN thickness as well as graphene doping, is required for the design of the most efficient SAW-mediated plasmonic devices.

Figure 7 shows the evolution of the strength (expressed as the maximum value of the peak in the $\Delta T^{TM}$ spectra) of the different SPPP, and HPPP, induced by a SAW with $\lambda_{SAW} = 250\,\text{nm}$ for $E_F$ varying from 0.1 eV to 0.6 eV and for different thicknesses of the h-BN interlayer. For thin h-BN films, the maximum of SPPP$_1$, figure 7(a), occurs at energies below $\omega_{TO}^{TM}$ as the SPPP$_1$ cannot propagate into the reststrahlen band of AlN. However, for thicker h-BN layers, this boundary
condition relaxes and the maximum occurs at energies beyond $\omega_{h\text{BN}}^{LO}$ but below $\omega_{h\text{BN}}^{TO}$, as now is the lower reststrahlen band of h-BN the one effectively limiting the propagation of SPPP₁. In all cases, the appearance of a maximum as $E_F$ increases is related to the existence of two competing mechanisms, since a larger carrier density makes the plasmon stronger while its shift to higher energies is stopped by either one of the reststrahlen bands. The behaviour of SPPP₂ and SPPP₃, figure 7(b), is more complex as it is affected by both the hBN reststrahlen band and the lower reststrahlen band of h-BN. As shown in figure 2(c) for a 1-nm thick h-BN interlayer, SPPP₂ appears very close to $\omega_{h\text{BN}}^{LO}$ and is very weak. In order to benefit from its large lifetime, it is required to increase the h-BN interlayer thickness above 10 nm, as shown in figure 7(b) and its magnified view in figure 7(d), while keeping $E_F$ low. In this regime, SPPP₂ evolves from $\omega_{h\text{BN}}^{LO}$ onwards as $E_F$ increases. However, for the $k$ value imposed by the selected SAW, there is a transition from SPPP₂ to SPPP₁ at a certain threshold value of $E_F$. The threshold value that produces this peak or saturate when evolving further towards $E_F$ lies within the reststrahlen band of h-BN, so that the lower reststrahlen band of h-BN, $\omega_{h\text{BN}}^{TO}$, appears very close to $E_F$.

Increasing the h-BN thickness reduces the energy range covered by SPPP₂ as the influence of AlN in the graphene/h-BN/AlN heterostructure reduces. The inset of figure 7(b) shows the evolution of HPPP₁ and HPPP₂, which are only observed for the 50 and 70 nm-thick h-BN interlayers for the $k$ value considered. These HPPP₁ modes are expected to be confined within the lower reststrahlen band of h-BN. However, it can be seen that HPPP₁ extends slightly below $\omega_{h\text{BN}}^{TO}$. This seems to be related to the fact that the lower reststrahlen band of h-BN lies within the reststrahlen band of AlN, so that the lower limit imposed by $\omega_{h\text{BN}}^{TO}$ relaxes. The exact mechanism behind this is still unclear. In case of SPPP₄, figure 7(c), its strength increases monotonically with increasing $E_F$ for all h-BN thickness values, as no boundary condition limits it. Conversely, HPPP₁ and HPPP₂, which are only observed for the 50 and 70 nm-thick h-BN interlayers for the $k$ value considered (inset of figure 7(c)), appear confined within the upper h-BN reststrahlen band. These HPPP₁ modes are thus expected to peak or saturate when evolving further towards $\omega_{h\text{BN}}^{LO}$, if a broader parameter range is considered. In summary, figure 7 shows that, within the range of the parameter space studied, the graphene/h-BN/AlN heterostructure provides SPPP₃ and

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**Figure 7.** Evolution of the strength (expressed as the maximum value of the peak in the $\Delta T_{TM}$ spectra) of (a) SPPP₁, (b) SPPP₂ and SPPP₃, and (c) SPPP₄ with $E_F$ for graphene/h-BN/AlN systems with carrier mobility $\mu = 10000$ cm² V⁻¹ s⁻¹ and various h-BN film thickness $d$ in the presence of a SAW ($m = 1$, $\delta = 4$ nm, and $\lambda_{SAW} = 250$ nm). (d) Zoom-in view of the box in (b). The solid circles represent the SPPP₃ mode whereas hollow circles correspond to the SPPP₂ mode. Insets in (b) and (c) show magnified views of the modulation of the HPPP₁ and HPPP₂, respectively, that appear for the 50 and 70 nm thick h-BN interlayers. $E_F$ varies in all cases from 0.1 to 0.6 eV in steps of 0.02 eV in the direction of the arrow.
5. Conclusions

In conclusion, we have theoretically demonstrated that SAWs can be used to generate SPPPs and HPPPs in graphene/h-BN heterostructures on a piezoelectric substrate, such as AlN, where the SAW creates a dynamic virtual diffraction overcoming the wave vector mismatch of SPPPs and HPPPs with the incident light. Graphene electrons couple to surface phonons of both the h-BN interlayer and the AlN substrate providing a complex SPPP dispersion relation that strongly depends on the thickness of the h-BN film and can be modulated by varying the Fermi energy of graphene. In addition, hyperbolic phonons appear in the case of multilayer h-BN films that also couple with the graphene carriers leading to tunable HPPPs. The h-BN interlayer is demonstrated to not only significantly change the hybridized SPPP dispersion but also to enhance the SPPP lifetime, as compared to the simpler graphene/AlN system. The lifetime enhancement provided by the h-BN film is shown to be related to both the higher carrier mobility induced in graphene and the larger lifetime of the h-BN surface phonons. Therefore, the graphene/h-BN/AlN system provides an advantageous platform with greater plasmon robustness and tunability for future SAW-based plasmonic devices.

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