Ultrasensitive plasmonic biosensors based on halloysite nanotubes/MoS_2/black phosphorus hybrid architectures

Guang Yi Jia,*[a] Zhen Xian Huang,[a] Yong Liang Zhang,[b] Zhi Qiang Hao[a] and Ya Li Tian[a]

[a]School of Science, Tianjin University of Commerce, Tianjin 300134, PR China.

[b]Department of Applied Physics, The Hong Kong Polytechnic University, Hong Kong, PR China.

*Email addresses: gyjia87@163.com

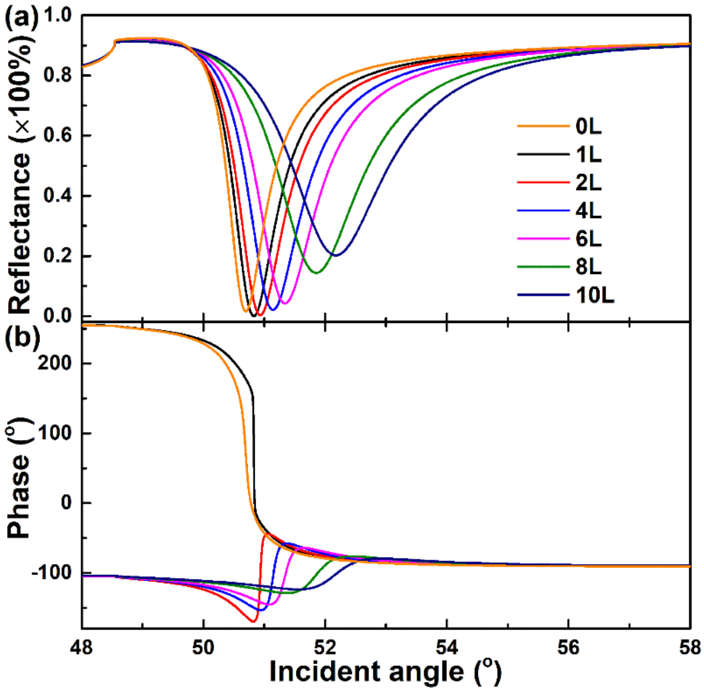

Fig. S1 Variations of (a) reflectance and (b) phase with respect to the incident angle by changing the layer number of MoS_2 film. The refractive index of initial calibration biosensing medium is $n_s = 1.333$ RIU. Layer number of BP, thicknesses of HNTs and gold films are 3L, 400 and 40 nm, respectively.

Transfer matrix method for calculating the decay curve of evanescent field

Within this framework of transfer matrix method,[1,2] it is assumed that there are two perpendicular magnetic field components with amplitudes $B_{j\mathrm{up}}$ and $B_{j\mathrm{down}}$ to propagate up (positive z) and down (negative z) in the jth medium, respectively. In the semi-infinite materials there is only one wave going in positive z after the N+1 boundary and negative z before the first boundary. Then the boundary conditions of the electromagnetic field can be described via using a matrix form as $AB = 0$ where

$$A=\begin{pmatrix} -1 & e^{-ik_{z1}d_1} & e^{ik_{z1}d_1} & 0 & & \cdots & & & 0 \\ 0 & -1 & -1 & e^{-ik_{z2}d_2} & e^{ik_{z2}d_2} & 0 & \cdots & & 0 \\ \cdots & & & & & & & \cdots & \\ 0 & 0 & 0 & \cdots & & 0 & -1 & -1 & 1 \\ \frac{k_{z0}}{n_0^2} & -\frac{k_{z1}}{\eta_1^2}e^{-ik_{z1}d_1} & \frac{k_{z1}}{\eta_1^2}e^{ik_{z1}d_1} & 0 & & \cdots & & & 0 \\ 0 & \frac{k_{z1}}{\eta_1^2} & -\frac{k_{z1}}{\eta_1^2} & -\frac{k_{z2}}{\eta_2^2}e^{-ik_{z2}d_2} & \frac{k_{z2}}{\eta_2^2}e^{ik_{z2}d_2} & 0 & \cdots & & 0 \\ \cdots & & & & & & & \cdots & \\ 0 & 0 & 0 & \cdots & & 0 & \frac{k_{zN}}{\eta_N^2} & -\frac{k_{zN}}{\eta_N^2} & \frac{k_{zN+1}}{n_{N+1}^2} \end{pmatrix} \tag{1}$$

$$B = \begin{pmatrix} B_{0\text{up}} \\ B_{1\text{up}} \\ B_{1\text{down}} \\ B_{2\text{up}} \\ \vdots \\ B_{N-1\text{down}} \\ B_{N\text{up}} \\ B_{N\text{down}} \\ B_{N+1\text{down}} \end{pmatrix} \tag{2}$$

In the above expressions, A is a $(2N+2) \times (2N+2)$ matrix and B is a vector of length $(2N+2)$. The complex wave vector k_j holds the momentum conservation $k_j^2 = k_x^2 + k_{zj}^2$ where k_x is the tangential component (along the surface) for all materials and k_{zj} is the perpendicular component varying dependent on the jth material. The eigen mode of the system occurs when the determinant of the matrix A equals 0 with a nonzero vector B. Then it is possible to solve the real and imaginary parts of k_x for each frequency of interested plasmonic surface wave.

Once the k_x value is found, the corresponding field coefficients can be solved by using the same equations. The overall field amplitude is arbitrary, so one can assign a value to one coefficient, such as $B_{0\text{up}} = 1$, and get a new system of equations $A_2B_2 = C$, with A_2 of size $(2N+2) \times (2N+1)$, B_2 of length $(2N+1)$ in length and C of length $(2N+2)$. The new matrix A_2 becomes

$$A_2 = \begin{pmatrix} e^{-ik_{z1}d_1} & e^{ik_{z1}d_1} & 0 & & & \cdots & & 0 \\ -1 & -1 & e^{-ik_{z2}d_2} & e^{ik_{z2}d_2} & 0 & \cdots & & 0 \\ \cdots & & & & & & & \cdots \\ 0 & 0 & \cdots & & 0 & -1 & -1 & 1 \\ -\frac{k_{z1}}{\eta_1^2}e^{-ik_{z1}d_1} & \frac{k_{z1}}{\eta_1^2}e^{ik_{z1}d_1} & 0 & & & \cdots & & 0 \\ \frac{k_{z1}}{\eta_1^2} & -\frac{k_{z1}}{\eta_1^2} & -\frac{k_{z2}}{\eta_2^2}e^{-ik_{z2}d_2} & \frac{k_{z2}}{\eta_2^2}e^{ik_{z2}d_2} & 0 & \cdots & & 0 \\ \cdots & & & & & & & \cdots \\ 0 & 0 & \cdots & & 0 & \frac{k_{zN}}{\eta_N^2} & -\frac{k_{zN}}{\eta_N^2} & \frac{k_{zN+1}}{n_{N+1}^2} \end{pmatrix} \tag{3}$$

Then the vectors B_2 and C become

$$B_2 = \begin{pmatrix} B_{1\mathrm{up}} \\ B_{1\mathrm{down}} \\ B_{2\mathrm{up}} \\ \vdots \\ B_{N-1\mathrm{down}} \\ B_{N\mathrm{up}} \\ B_{N\mathrm{down}} \\ B_{N+1\mathrm{down}} \end{pmatrix}, \qquad C = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ -\frac{k_{z0}}{\eta_0^2} \\ 0 \\ \vdots \\ 0 \end{pmatrix} \tag{4}$$

This system will be overdetermined since there is one more equation than parameters to solve for. The overdetermined system can be solved by the least squares formula

$$B_2 = [A_2' A_2]^{-1} A_2' \mathrm{C} \tag{5}$$

Thus, the field coefficients can be obtained for the p-polarized excitation light. This means that one can plot the electric field E against z within each material with

$$E_z(x,y) = -\frac{k_{x\,j}}{\eta_j^2} B_{j\mathrm{up}} e^{i\left[k_{z\,j}[z-Zj]+k_{x\,j}x\right]} + \frac{k_x}{\eta_j^2} B_{j\mathrm{down}} e^{-i\left[k_{z\,j}[z-Zj]+k_{x\,j}x\right]} \tag{6}$$

$$E_x(x,y) = \frac{k_{z\,j}}{\eta_j^2} B_{j\mathrm{up}} e^{i\left[k_{z\,j}[z-Zj]+k_{x\,j}x\right]} - \frac{k_z}{\eta_j^2} B_{j\mathrm{down}} e^{-i\left[k_{z\,j}[z-Zj]+k_{x\,j}x\right]} \tag{7}$$

Here Zj is simply the reference z coordinate at the interface of the (j-1)th and jth media.

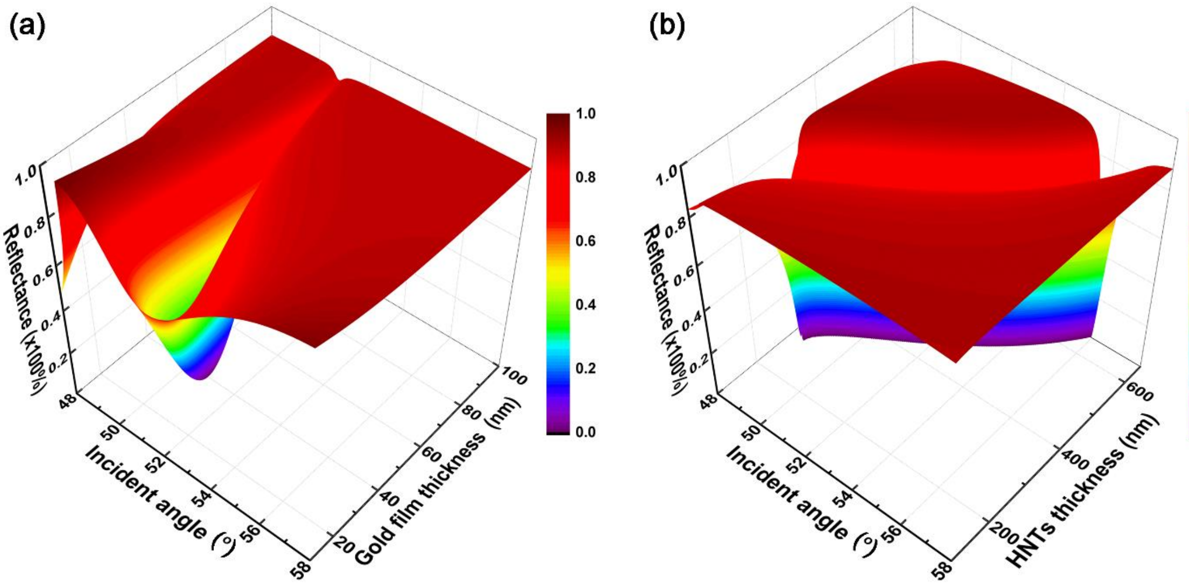

Fig. S2 Reflectance spectra of the proposed biosensors with the configuration of HNTs/1L MoS_2/3L BP/Au/prism. The refractive index of biosensing medium is set as n_s = 1.333 RIU. The thickness of HNTs in (a) is 400 nm. The thickness of gold film in (b) is 40 nm.

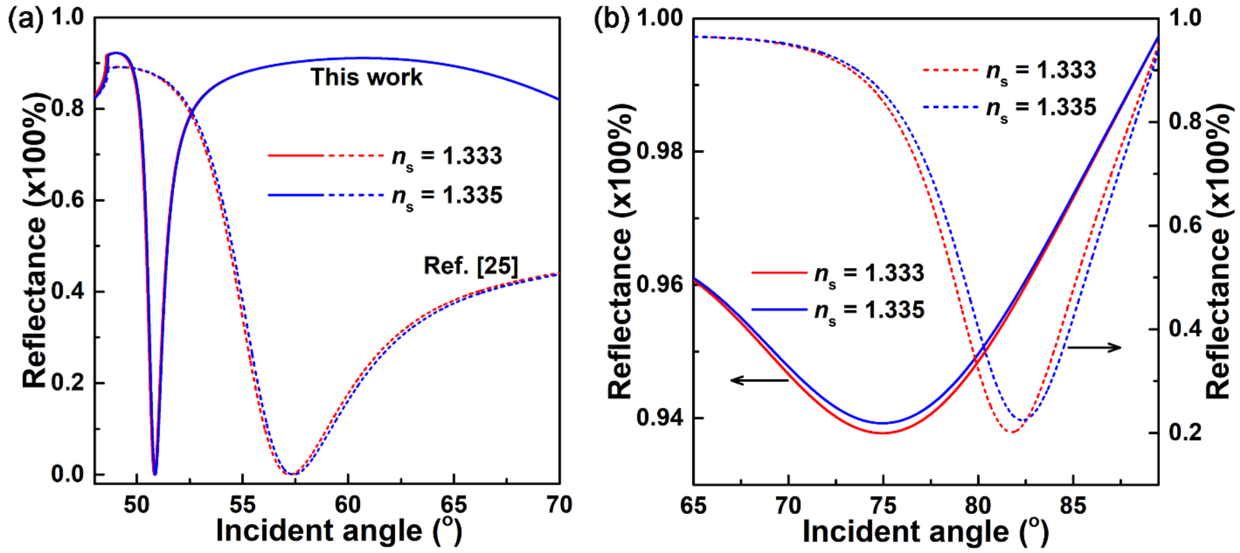

Fig. S3 (a) Reflectance spectra of biosensors proposed by us (solid lines, corresponding to the structure of 400 nm HNTs/1L MoS_2/3L BP/40 nm Au/SF11 prism) and Ref. [25] (dashed lines, corresponding to the structure of 1L Graphene/4L BP/48 nm Au/100 nm BK7/SF11 prism). (b) Reflectance spectra of the biosensor configuration of 2L WSe_2/5 nm BP/50 nm Ag/BK7 prism. The solid lines are calculated by considering the optical anisotropy and polarization dependent refractive index of BP. The dashed lines are calculated by using the fixed refractive index $n_{BP} = 3.5 + 0.01i$ which is utilized by the authors in Ref. [23].

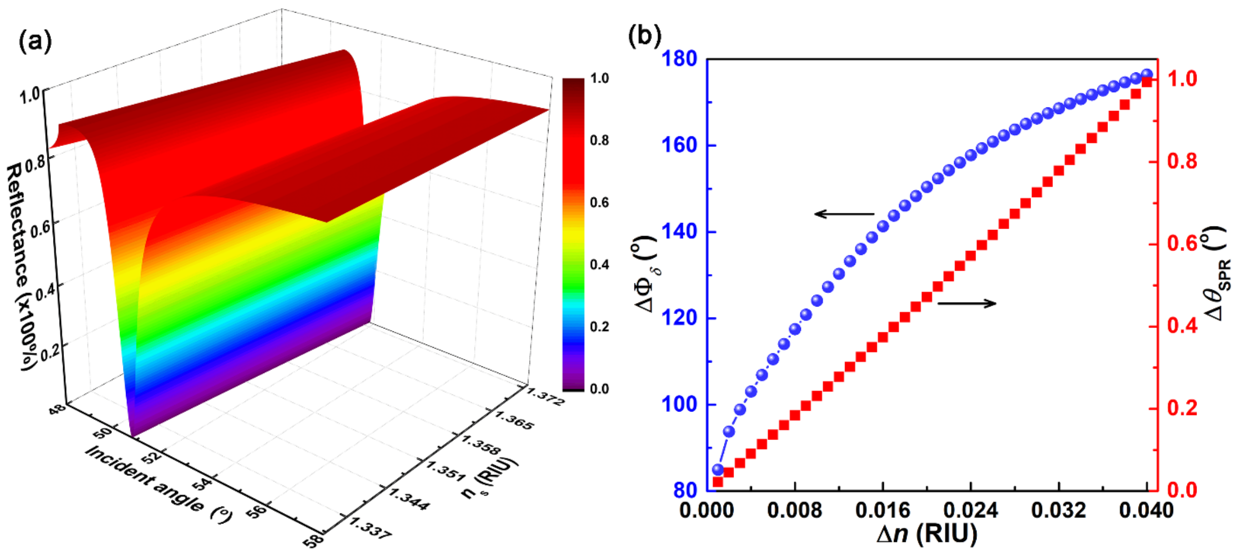

Fig. S4 (a) Variation of reflectance spectra with respect to the refractive index n_s of biosensing medium. (b) The change of phase difference $\Delta\Phi_\delta$ and the change of SPR angle $\Delta\theta_{SPR}$ at different refractive-index variates Δn. The refractive index of initial calibration biosensing medium is set as n_s = 1.333 RIU.

References

1 G. Y. Jia, Q. Zhang, Z. X. Huang, S. B. Huang and J. Xu, *Phys. Chem. Chem. Phys.*, 2017, **19**, 27259−27265.

2 A. B. Dahlin, M. Mapar, K. Xiong, F. Mazzotta, F. Höök and T. Sannomiya, *Adv. Optical Mater.*, 2014, **2**, 556–564.