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WS_2 quantum dot/Si heterojunction based self-biased photodetector with plasmon mediated suppressed dark current and fast photoresponse

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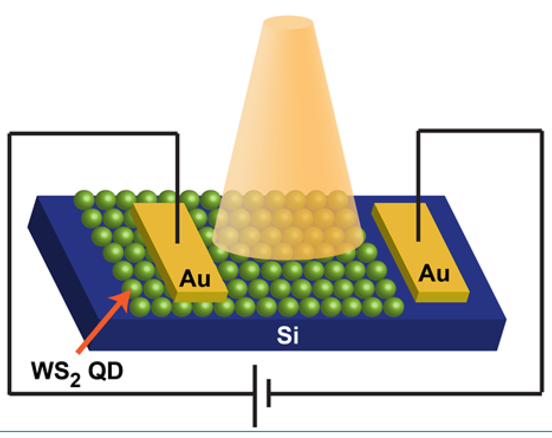
INTRODUCTION

- Van der Waals heterostructure based photodetectors built from WS_2 quantum dots (QDs) on a p-type Si platform.
- The WS_2 QD/Si photodetector (PD) can operate at zero bias owing to the separation of charge carriers by the built-in electric field.
- Integration of plasmonic Au nanoparticles (NPs) into the WS_2 QD/Si PD greatly improves the photodetector performance.

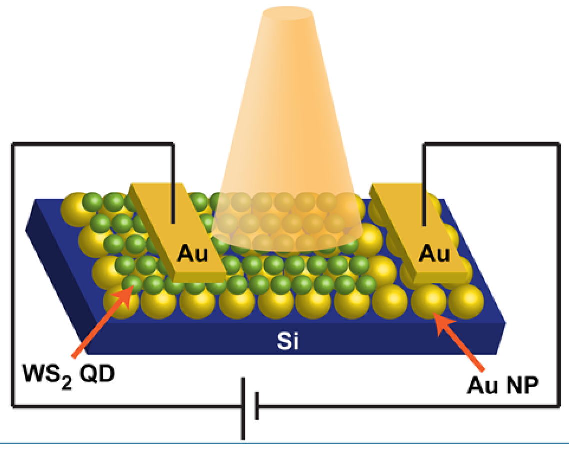
DEVICE FABRICATION



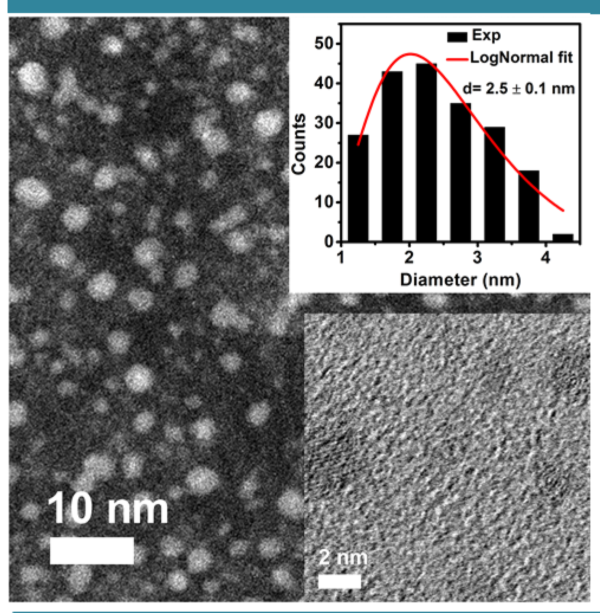
Schematic illustrations of

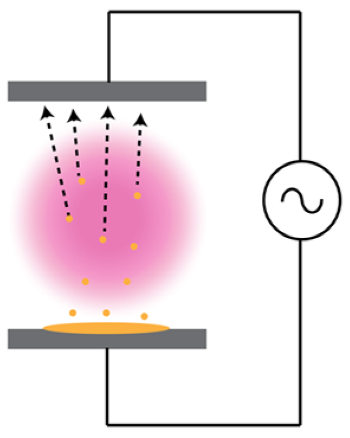
- ❑ WS_2/Si
- ❑ WS_2/Au/Si

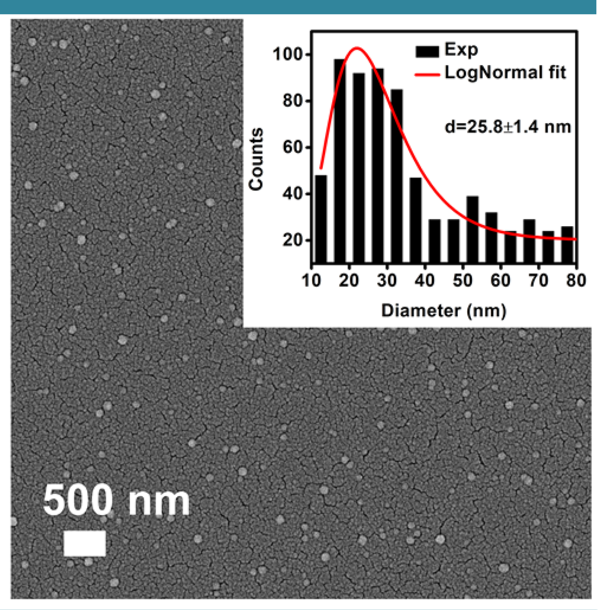
heterojunction photodetectors in reverse bias condition.



STRUCTURAL CHARACTERISTICS



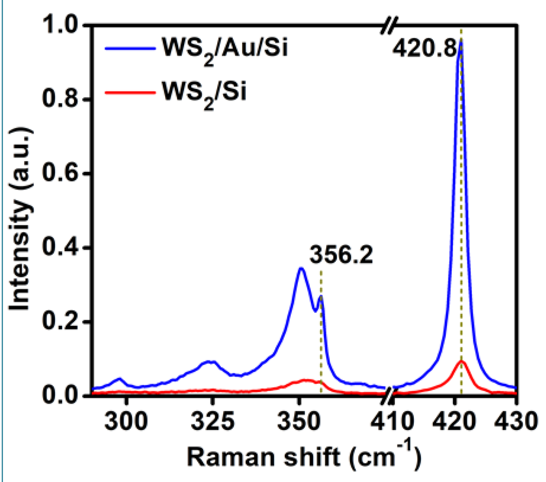




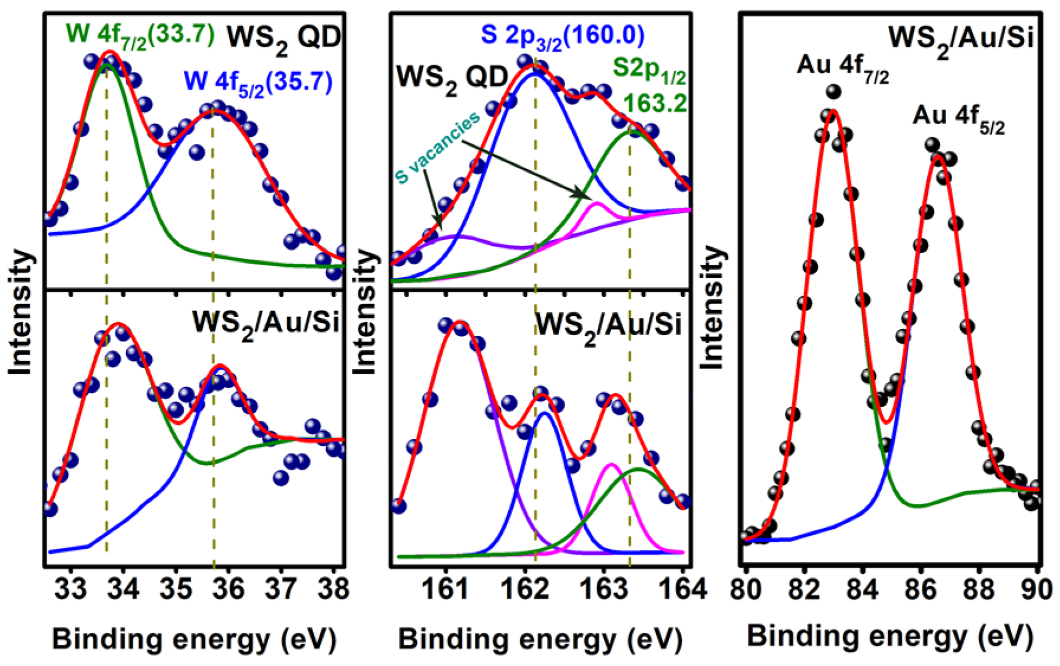
HAADF and HR-TEM:
QDs of average size 2.5 nm. Lattice d-spacing of 2.3 Å.

FESEM of Au NPs

- Au film deposition done by RF sputtering at -12V. Rapid thermal annealing done at 600 °C for 3 min.
- Average particle size ~ 25 nm.

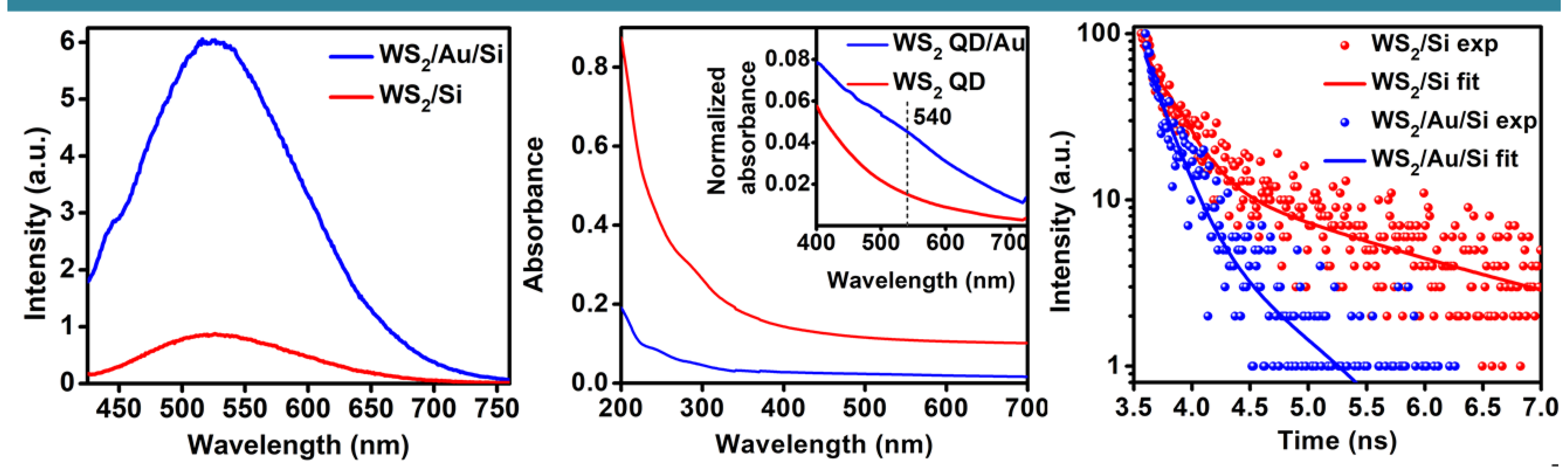


SERS effect due to Au NPs leads to a ~10 folds enhancement



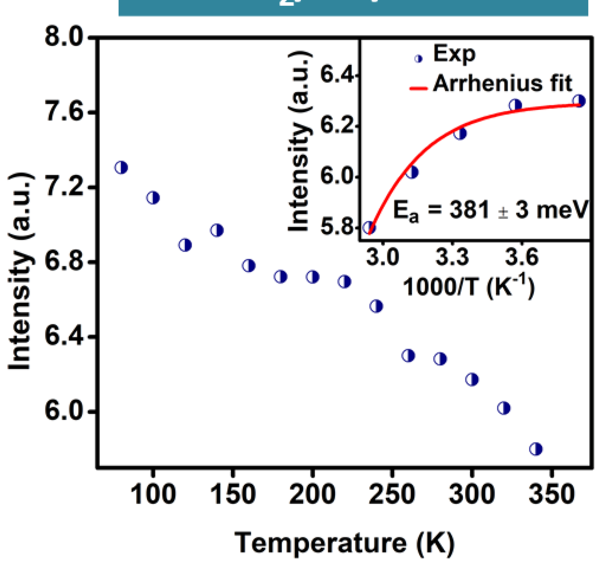
- The overall upshift of the binding energies of W and S indicates charge transfer or n type doping by Au NPs.
- The high resolution XPS peaks at 83.0 eV and 86.6 eV confirm the presence of elemental Au NPs.

OPTICAL CHARACTERISTICS

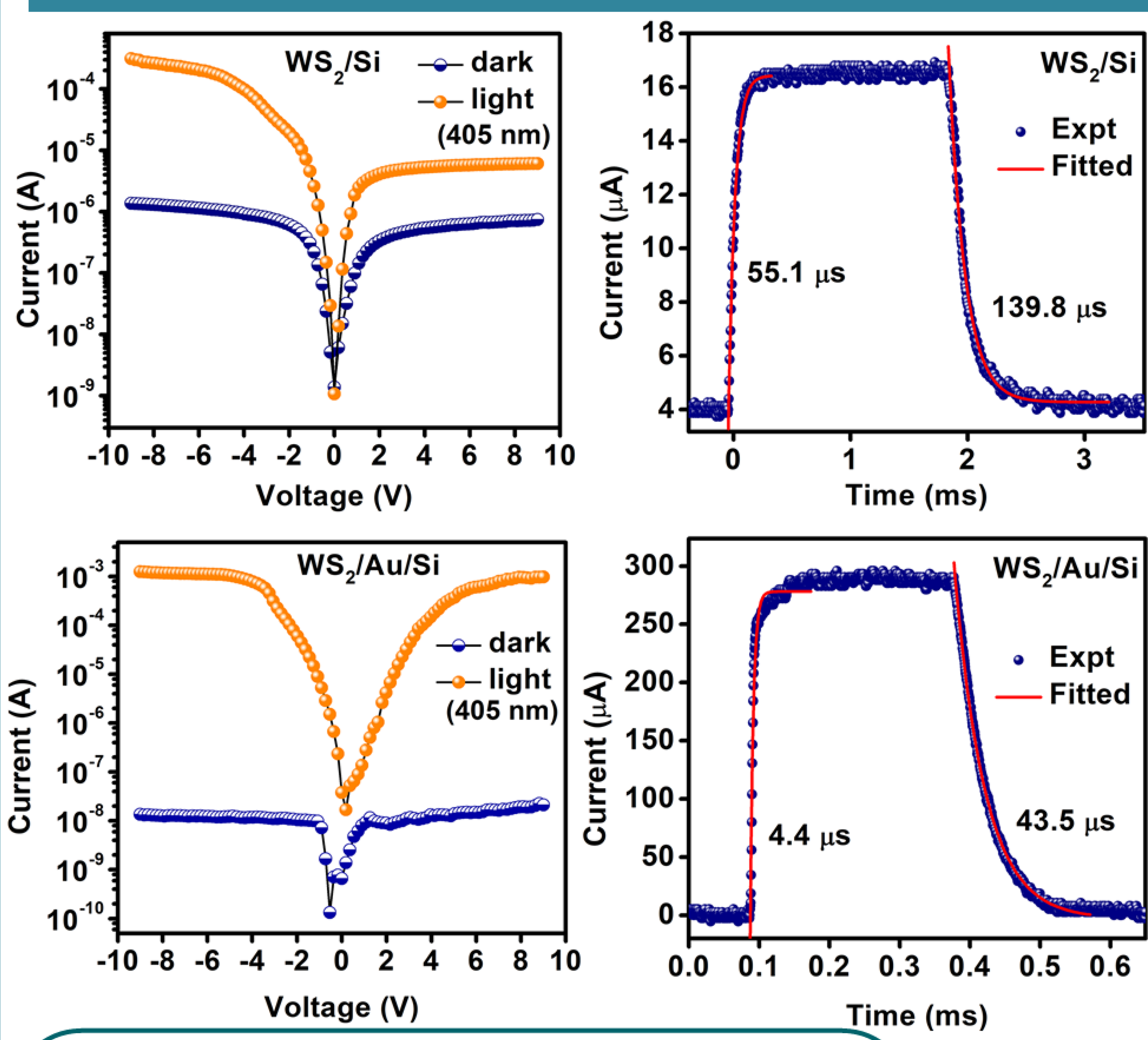


- There is ~6 fold PL enhancement of WS_2 QDs by Au NPs.
- The absorption hump at ~540 nm for WS_2/Au is induced by the creation and enhancement of the localized EM field or LSPR.
- Faster decay in WS_2/Au/Si due to high non-radiative decay rate from electron-plasmon interaction.
- High thermal activation energy (E_a) ~381 meV, thus, lesser the probability of thermal dissociation of excitons.

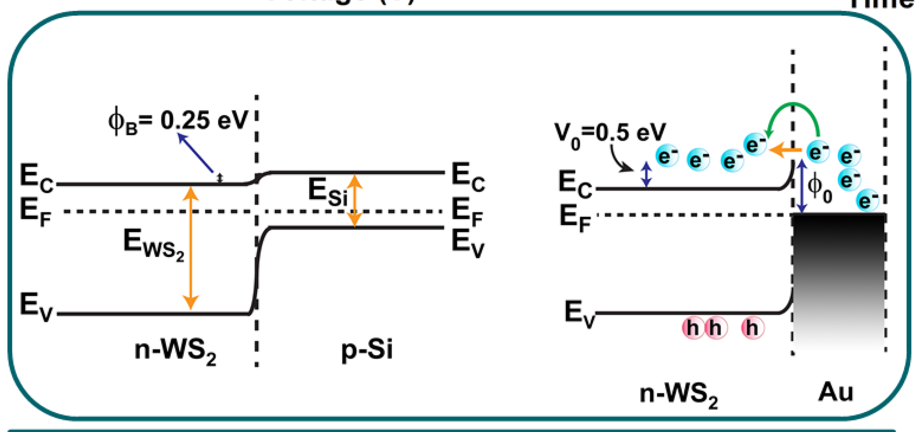
Temperature dependent PL of WS_2/Au/Si HS



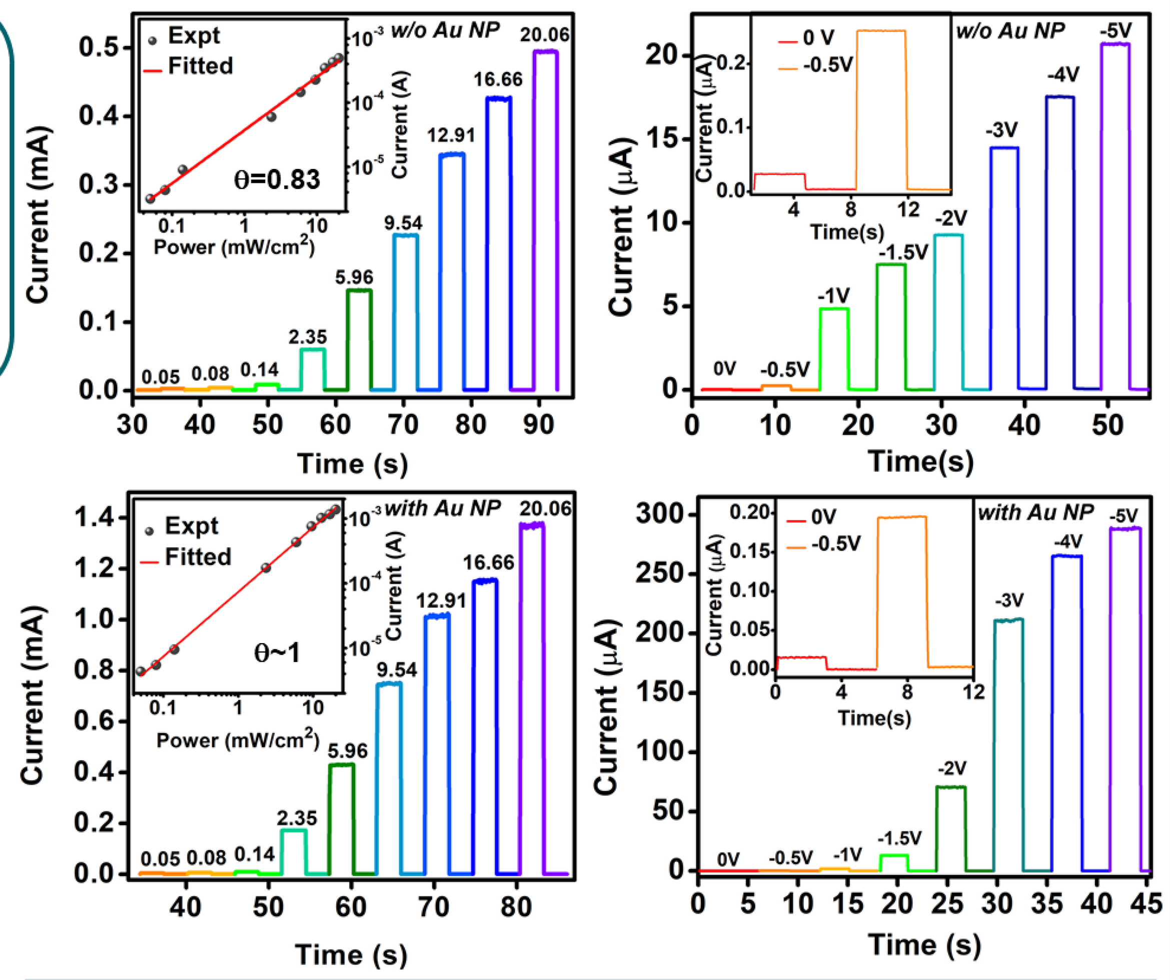
PHOTODETECTOR PERFORMANCE



- Asymmetric photo I-V in WS_2/Si shows rectifying behavior, with a high I_{on}/I_{off} ratio ~227.
- Symmetric photo I-V in WS_2/Au/Si indicates Schottky back to back contacts. The I_{on}/I_{off} ratio is ~1.3 ×10⁵.
- High E_a and sporadically scattered Au NPs layer ensures suppressed dark current in WS_2/Au/Si.
- The growth/decay time constants for WS_2/Si ~ 55.1/139.8 µs, whereas, for WS_2/Au/Si, it is ~ 4.4/43.5 µs.



- In WS_2/Si, a type II heterojunction is formed with potential barrier, ϕ_B ~0.25 eV. Upon illumination with 405 nm laser, charge transfer excitons are formed. The excitons dissociate aiding in charge separation.
- For WS_2/Au/Si, at the WS_2/Au interface, a Schottky junction is formed. At the p-Si/Au interface, an Ohmic contact is formed. A built-in potential of 0.5 eV (V_0) develops on the WS_2 side. The electrons from Au overcome the barrier height (ϕ_0=1.1 eV) to transfer to the CB of WS_2 QDs in 2 possible ways: (1) *Hot electrons* in the Au NPs, possessing sufficiently high energy. (2) *Tunneling electrons* that are able to pass through the depletion width, as the WS_2 QDs are monolayered (0.8 nm).
- Electron tunneling is highly elevated in the reverse bias. Also, as the E_F of the WS_2 QDs goes down, there is more effective hot electron transfer.



- Power law (I=P^θ) fitting yields sublinear behaviour (θ = 0.83) indicating presence of trap states in WS_2/Si.
- In WS_2/Au/Si, θ~1. The Au NPs between the WS_2 and the Si allows higher charge separation.
- V dependent photo responses of both PD show operation at 0 bias voltages. At 0 bias, the WS_2/Si has I_{on}/I_{off} of ~8, while WS_2/Au/Si exhibits a high I_{on}/I_{off} of ~280.

CONCLUDING REMARKS

WS_2 QD based vertical hybrid devices can be driven at zero bias. The incorporation of Au NPs serves as a carrier tunneling pathway and the generation of hot electrons for ultra-fast charge transport. The ununiform Au NP arrangement suppresses dark current which further elevates the photodetector performance.

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