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Density functional theory based study of chlorine doped WS$_2$-metal interface

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Investigation of a transition metal dichalcogenide (TMD)-metal interface is essential for the effective functioning of monolayer TMD based field effect transistors. In this work, we employ the Density Functional Theory calculations to analyze the modulation of the electronic structure of monolayer WS$_2$ with chlorine doping and the relative changes in the contact properties when interfaced with gold and palladium. We initially examine the atomic and electronic structures of pure and doped monolayer WS$_2$ supercell and explore the formation of midgap states with band splitting near the conduction band edge. Further, we analyze the contact nature of the pure supercell with Au and Pd. We find that while Au is physisorbed and forms n-type contact, Pd is chemisorbed and forms p-type contact with a higher valence electron density. Next, we study the interface formed between the Cl-doped supercell and metals and observe a reduction in the Schottky barrier height (SBH) in comparison to the pure supercell. This reduction found is higher for Pd in comparison to Au, which is further validated by examining the charge transfer occurring at the interface. Our study confirms that Cl doping is an efficient mechanism to reduce the n-SBH for both Au and Pd, which form different types of contact with WS$_2$. © 2016 AIP Publishing LLC.

We start by analyzing the electronic dispersion characteristics of pure and Cl-doped WS$_2$ and explore the shifts in the energy bands with respect to Fermi level ($E_F$) and further analyze the mid gap states formed near the conduction band (CB) edge. To preserve the stability in the $5 \times 5$ WS$_2$ supercell, the number of chlorine dopants substituting the sulfur atoms is kept one. We perform the formation energy calculations ($E_{form}$) to find the stability of the chlorine doped structure. Next, this supercell is interfaced with $\langle 111 \rangle$ cleaved surfaces of Au and Pd, respectively, and the contact nature is studied. The SBH is evaluated using the projected bandstructure and the density of states. The charge transfer across the interface is analyzed using the valence electron density and charge density difference. An electron localization function (ELF) is employed to study the localization of electrons at the WS$_2$-metal interface. A thorough examination of all the above analysis leads to a conclusion that n-type doping of WS$_2$ using chlorine as an effective substitute results in lowering of n-SBH at the WS$_2$-metal interface.

After the fabrication of field effect transistor (FET) using monolayer MoS$_2$, the 2D layered transition metal dichalcogenides (TMDs) have garnered enormous attention in the electronic devices community. Apart from MoS$_2$, other TMDs such as WSe$_2$, MoSe$_2$, MoTe$_2$, and WTe$_2$ are also explored as channel materials for FETs. In the absence of efficient doping techniques, these transistors exhibit Schottky barrier height (SBH) at the source/drain contact, which leads to a low ON current. Tremendous efforts are dedicated to reduce the contact resistance at the TMD-metal interface by employing different techniques both theoretically and experimentally. However, most of these efforts are focused towards MoS$_2$ and WSe$_2$, and a minimum study is devoted to other TMD’s-metal contact interfaces. A study using ballistic MOSFET model reveals that WS$_2$ outperforms all other TMDs. Experimental reports of WS$_2$ device fabrication and Cl doping technique for reducing WS$_2$-metal contact resistance are also reported. However, theoretical investigations of WS$_2$ metal contact interface using first principles is still lacking in the literature. Since first principles are extensively used to analyze the graphene-metal, MoS$_2$-metal, and WSe$_2$-metal, it is believed that it will efficiently describe the contact nature with other TMDs as well. For WS$_2$, chlorine doping, which is done by replacing sulfur atoms, is the first ever method demonstrated experimentally to reduce the WS$_2$-contact resistance, exhibiting both high drain current and field-effect mobility. In this work, we employ the density function theory (DFT) to study the electronic structure of the interface between WS$_2$ and one physisorped (Au) and one chemisorped metal. We then examine the effect of chlorine doping by substituting sulfur atoms to address the SBH mitigation at WS$_2$-metal interface.

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interface.27 To minimize false interactions between the peri-
unit cell and supercell of WS2.

We first confirm the band gap of WS2 unit cell and find the value to be 2.07 eV, nearly consistent with the earlier
reports.23,24 A 5 × 5 supercell is formed using the optimized
unit cell, which is computationally appropriate to study the
doping similar to the one reported here.25 The interface strain
between the pure and doped WS2 supercell with ⟨111⟩ cleaved
surface of gold and palladium is found to be 1.3% and 2.1%,
respectively. Doping is achieved by replacing one chlorine atom
with a chlorine atom in the supercell, which amounts to 2% of
the total sulfur atoms. For evaluating $E_{\text{form}}$ for sulfur substitu-
tion, $X_2$ dimers of each $Cl_2$ and $S_2$ are taken, and then, the
total energy of the substitutional atoms and host atoms in the
formation energy equation26 are calculated. Four layers of
⟨111⟩ cleaved surface of metal are then interfaced with the
WS2 supercell and is found relevant to study the MoS2-metal
interface.27 To minimize false interactions between the peri-
odic interfaced geometries, vacuum length of 20 Å is consid-
ered. A force optimization of (0.001 eV/Å) is performed for
both unit cell and supercell (pure and doped) of the WS2 using
the limited memory Broyden-Fletcher-Goldfarb-Shannon
(LBFGS) method. The volume of the structure is allowed to
change using a stress optimization of (0.001 eV/Å$^2$) in both
unit cell and supercell of WS2.

Figure 1(a) shows the stable atomic structure of chlorine
doped 5 × 5 supercell of WS2. We perform the formation
energy calculations to find the thermodynamically stable position
for sulfur substitution by chlorine atoms with the $E_{\text{form}}$
values as 2.92 eV. This supercell is interfaced with ⟨111⟩
cleaved surface of Au and Pd, respectively. While interfacing,
the lattice constant of WS2 is fixed and the metal slab is
subjected to match with it. Figures 1(c) and 1(d) show the ball
and stick model of the doped 5 × 5 WS2Au and WS2-Pd
interface. The total energy calculations reveal 2.7 Å and 2.2 Å
as the equilibrium interlayer separation between the WS2
(pure and doped) with Au and Pd metal slabs. The binding
energy values obtained per sulfur atom are $-0.18$ eV (pure)
and $-0.19$ eV (doped) for gold and $-0.39$ eV (pure) and
$-0.4$ eV (doped) for palladium, respectively. We calculate the
work function of the pure and doped WS2, and metals Au and
Pd and are shown in Figure 1(f).

Substituting by chlorine doping amounts to 2% of total
sulfur atoms, which leads to a very high doping concentra-
tion in a 5 × 5 supercell of WS2. However, to realize the
substitution by considering the experimental doping concentra-
tion value of $6 \times 10^{11}$ cm$^{-2}$ studied here,14 a much bigger
supercell is required, leading to a further increase in computa-
tional burden. To reduce the computational cost and study
the effect of doping on SBH reduction, we limit ourselves
with a 5 × 5 supercell.

The electronic structures of both the pure and doped WS2
along with the density of states are compared in Figure 2 to
highlight the effect of doping. The band gap of pure WS2 is
2.07 eV. The positions of CB and Valence Band (VB) are
verified with PDOS kept along the side of bandstructure. We
see that substituting a single chlorine dopant shifts the energy
bands towards the $E_F$ and creates the midgap states in the vi-

cinity of $E_F$. The number of midgap states is 2, one of which
splits into two bands between the high symmetry points of
Brillouin zone shown in the inset of Figure 2(c). The two mid

gap states have significant contribution in the PDOS as well.
The main contributor of these states is chlorine, which is
shown in the inset of Figure 2(d) with purple color. The energy
level is 0.184 eV for the midgap state near the conduc-
tion band minima (CBM). The splitting of bands leads to two
energy levels of 0.028 eV and 0.020 eV, respectively. These
defect states originate from the hybridization of the Cl 3p
and the W 5d states. There exists one unpaired extra electron
due to n-type doping by chlorine. As tungsten lies in the 6th pe-
riod of the periodic table, chlorine, which has an extra nega-
tive charge, leads to the energy splitting of W d-orbitals and
thus contributes to an extra midgap state. The band gap in
doped WS2 is also different as compared to the pure supercell
(by 0.05 eV), which is attributed to the hybridization and change
in the atomic structure due to chlorine substitution.

We then perform simulations to evaluate the nature of contact
formed with WS2 (pure and doped) with Au and Pd. The
Schottky barrier height is assessed using the electronic
structure and DOS of the projected WS2. The valence elec-
tron density and charge density difference are used to
The nature band gap is lost, and the projected band structure and doped (with Au and Pd) are shown in Figures 3(a)–3(d).

**FIG. 2.** Projected bandstructure and DOS of (a) and (b) pure WS$_2$ and (c) and (d) chlorine doped WS$_2$. PDOS placed along the side verifies the position of CB and VB. Doping with chlorine leads to the appearance of midgap states in the WS$_2$ band gap and their contribution is studied using the DOS. The number of midgap states is 2 for doped WS$_2$. The inset in (c) shows the exact position of CBM and the midgap states. The purple line in (d) shows the chlorine contribution in PDOS and is highlighted in the inset. The contribution of midgap states is confirmed by the PDOS, and the peaks in PDOS occur at the same energy level as in the bandstructure. CB, VB, $E_F$, and $E_g$ denotes the conduction band edge, valence band edge, Fermi level and band gap, respectively. Fermi level is at zero energy. The dashed brown lines join the CBM and VBM in the bandstructure and DOS.

estimate the charge transfer across the interface. The localisation of electrons at the WS$_2$-metal interface is studied using the ELF.

Both the p- and n-type SBH of the projected WS$_2$ (pure and doped) with Au and Pd are shown in Figures 3(a)–3(d). Since the interface involves two different atomic structures, the nature band gap is lost, and the projected band structure comprises of interface states. The origin of these states lies in the complex electronic hybridization occurring at the WS$_2$-metal interface. Au is found to be physisorbed with WS$_2$ whereas Pd is chemisorbed. Au, being an s-electron metal, shows less hybridization as compared to Pd, which is a d-electron metal, and this effect is similar to MoS$_2$-metal interface. The binding energy values quoted earlier confirm this nature. Moreover, the band gap regime also consists of less interface states in Au as compared to Pd (Figures 3(a) and 3(c)).

For a pure WS$_2$-Au interface, the amount of complexity in the bandstructure is less, but for a doped interface, it is very high. This happens because the atoms in the doped supercell already hybridize with the substitutional impurity. The difference is visible in Figures 3(b) and 3(d) with respect to Figures 3(a) and 3(c). It further makes the determination of band gap edges difficult. However, the density of states along with the electronic structure of projected WS$_2$ can be used to identify the CBM and valence band maxima (VBM), as demonstrated in Ref. 8. The difference between the CBM and VBM of all the interfaces differs from the band gap of pure WS$_2$ by 0.04 eV. Strong interface hybridization causes emergence of more midgap states for both the pure and doped supercells as visible in Figures 3(c) and 3(d) for Pd due to its chemisorption nature with WS$_2$. We observe that Au shows an n-type SBH and Pd shows p-type SBH when interfaced with WS$_2$. The values of SBH are 0.78 eV and 0.76 eV, respectively. In the complete band structure shown by grey lines, we see that for Au the band lines are more dispersed in comparison to Pd. This indicates a strong bonding of WS$_2$ with Pd. Moreover, below the Fermi level, we see a complete metallization for Pd, leading to the formation of the p-type contact. Here, we see a similarity in the nature of contact between WS$_2$ and WS$_2$ while forming an interface with Au and Pd. With the introduction of n-type impurity, the n-SBH exhibits a reduction for both metals. The n-SBH reduction attained is 0.09 eV for Au and 0.11 eV for Pd. We see that the reduction in the n-SBH is higher for Pd in comparison to Au. Pd showing a p-type contact with WS$_2$ also exhibits a reduction in the n-SBH and increase in p-SBH. This validates the observation that the chlorine is effective in reducing n-SBH for both the types of metals forming p- and n-type SBH with WS$_2$ and is equally competent for chemisorbed and physisorbed metal interface with WS$_2$. A slight variance in the band gap value of WS$_2$—2.07 (for pure WS$_2$ bandstructure)–2.1 and 2.09 (projected WS$_2$ bandstructure) is also observed due to heterogeneous atomic interface.

We also evaluate the valence electron density for the WS$_2$-metal interface, as shown in Figure 4. The value of valence electron density is calculated as the minimum electron density at the metal-semiconductor interface. Higher values of electron density at the interface imply a better electron injection efficiency. The values with Au are for pure 0.10727 Å$^{-3}$ and 0.10816 Å$^{-3}$ for doped supercell. For pure and doped supercell with Pd, they are 0.21888 Å$^{-3}$ and 0.2212 Å$^{-3}$, respectively. The high values for Pd indicate that more charge transfer has occurred when it is interfaced with WS$_2$. Moreover, the difference in the density values of the doped and pure interface is higher for Pd as compared to those for Au.
To substantiate the observations made in the above analysis, we examine the charge density difference of the respective geometries. Figure 5 shows the average charge density difference of the WS$_2$-metal interface for (a) Au and (b) Pd. A dipole gets created at the interface since both accumulation and depletion regions exist. Both the regions are shown by dissimilar colors to highlight the difference between them. At the junction between the nearest sulfur atom and metal atom, two peaks exist for the depletion region and one peak for the accumulation region. Moreover, the accumulation shows a higher charge difference in Pd as compared to Au. A higher depletion regime implies that the charge carriers are repelled back from the surface and evinces a probability of least transmission across the interface. On the other hand, a higher accumulation regime implies that more charge is transferred across the interface. Hence, we observe more hybridization for Pd rather than Au. The area calculated between the nearest S and metal atom using the methodology exhibited in Ref. 8 is $0.03181 \times 10^{-3}$ for Au and $0.06031 \times 10^{-3}$ for Pd, respectively, and thus affirms the charge transfer is high for Pd. For the pure and doped supercell-metal interface, the charge density difference curve shows a similar nature and the difference in areas for the pure and doped case is higher for Pd. Because of this difference, a greater reduction in n-SBH is observed in Pd with respect to Au.

To study the localization of electrons at the WS$_2$-metal interface, we study ELF, which is a dimensionless quantity. It is defined as the possibility of finding an electron in the neighborhood of a reference electron. Its value ranges from $0 \leq \text{ELF} \leq 1$, with the maximum limit ELF = 1 corresponding to a perfect localization and ELF = 0.5 corresponding to an electron-gas like pair probability. Figure 6 shows the value of ELF for the WS$_2$-Au and WS$_2$-Pd interface. The value obtained for Pd is less when compared to Au. This implies that Au is more localized than Pd, indicating a better bonding for the WS$_2$-Pd interface.

It is interesting to note that for TMD channel based transistors, in a top contact device structure, two types of interfaces exist. One interface is between the TMD-metal and the other is between the TMD underneath the metal contact and TMD forming the channel. Here, we find the SBH formed at the first interface. For calculating the SBH at the second interface, transport simulations need to be conducted along the device length. The effective SBH combining both the interfaces can then be determined using LDOS distribution. However, carrying transport simulations employing pseudo-potentials with basis functions having higher orbital contributions requires a powerful computing system, as the number of atoms increases manifold from the bulk-configuration to device-configuration. Nevertheless, while discussing SBH and the associated contact resistance in the context of ON current of the MOSFET, the gate current is kept high, and the channel is inverted. In this condition, the CBM of the TMD channel region (not touching the metal) can be assumed to be lower than the CBM of the other TMD regime. Hence, the SBH evaluated in this work can be considered as the effective SBH.

In the above study, we investigate the contact nature of the pure and Cl doped monolayer WS$_2$ with Au $\{111\}$ and Pd $\{111\}$. First, the electronic structures of pure and doped supercells are investigated. We find that the band energies near to the conduction band edge align close to Fermi level with the formation of midgap states and band splitting. Further, the pure and doped optimized supercell are adsorbed on the metals. The interface with pure supercell determines that Au is physisorbed with WS$_2$ and has an n-type SBH while Pd is chemisorbed with WS$_2$ having a p-type SBH. Adsorption with the Cl doped supercell shows a reduction in the n-type SBH for both the metals. All the results are validated by studying charge redistribution at the WS$_2$-metal interface. The above understanding may further contribute to explore other TMD-metal interfaces, as well as in investigating various possible dopants for chalcogenide substitution.
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