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Microarticle

A new method of carrier density measurement using photocurrent maps of a 2D material Schottky diode

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ABSTRACT

A simple method for obtaining the charge carrier density of two-dimensional (2D) materials is proposed herein. A formula is suggested for the extraction of the 2D charge carrier density using the horizontal depletion width, which is visually represented by photocurrent mapping methods. An example of this method is demonstrated using a MoS_2 Schottky diode. The results suggest that this method can be useful for a basic analysis of the physical properties of 2D devices.

Introduction

Two-dimensional (2D) materials with laterally-defined active channels are emerging as new semiconductor materials for device applications due to their excellent electrical and optical properties [1]. The characterization of these channel materials is an important topic as it relates to device performance. Specifically, the device performance can be adjusted by controlling the channel properties via the influence of the external environment (e.g. growth method, doping, device process conditions etc.) upon the carrier concentration. This, in turn, requires quick and easy characterization. However, in comparison to the measurement of 3D bulk semiconductor materials, the use of conventional Hall effect and C-V measurement methods to obtain the carrier density of 2D materials incurs many difficulties relating to the fabrication and examination of samples [1]. For these reasons, the carrier density is generally obtained from the relationship between the effective mobility and the conductivity obtained from field-effect transistor-like devices. In the present study, a simple model is proposed for obtaining the effective 2D carrier density directly via photocurrent mapping of a 2D Schottky diode using the photovoltaic effect in the horizontal depletion area. As a practical example, the extraction methods are demonstrated for the carrier density of a lateral 2D Pt/MoS_2 Schottky diode.

Model and methods

A simple analytic model of the lateral metal-2D semiconductor Schottky junction is applied on the basis of the full depletion approximation. Due to the tiny thickness of the 2D material, it is assumed that the vertical depletion width, W_{dz}, is equal and/or confined to the 2D material thickness, t, as shown schematically in Fig. 1(a). Hence, the horizontal depletion width, $W_{h,x}$, can be expanded laterally as the Schottky junction area even under 0 bias voltage. Therefore, the general electrostatic potential, $\varphi(x)$, of the horizontal depletion region of the 2D Schottky diode (SD) can be obtained from the 1D-Poisson's equation, Eq. (1):

$$\nabla^2\varphi(x) = -\frac{\rho(x)}{\varepsilon} \tag{1}$$

where ρ(x) is the charge density and ε is the permittivity [2].

Moreover, in the metal/2D-semiconductor junction area, the charge in the semiconductor, Q_d, should be exactly balanced by the charge in the metal Q_M, as summarized in Eq. (2):

$$Q_M = Q_d = qtN_d \tag{2}$$

where t is the thickness of the 2D material, q is the basic charge, and N_d is the carrier density.

The horizontal depletion width, $W_{h,x}$, can then be defined as Eq. (3):

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$$W_{h,x} = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{q}\left(\frac{1}{tN_d}\right)(V_{h,bi} - V_a)} \quad (3)$$

where ε_r and ε_0 are dielectric constant and vacuum permittivity, respectively, and $V_{h,bi}$ is horizontal built-in voltage [2].

The measured $W_{h,x}$ value obtained from the photocurrent maps is then used to obtain the carrier density, N_d, from Eq. (4):

$$N_d = \frac{2\varepsilon_r\varepsilon_0 V_{h,bi}}{q}\frac{1}{tW_{h,x}^2} \quad (4)$$

where the $V_{h,bi}$ term can be replaced with the $V_{turn\text{-}on}$ value of the *I-V* curve [2].

The Pt/MoS_2 Schottky barrier junction was formed by placing a 20-nm-thick MoS_2 flake on Pt metal following the detailed device fabrication methods given in previous work [3]. The photocurrent mapping equipment was customized using the XperRAM system [4,5]. As summarized in Table 1, the photocurrent maps were obtained at a reverse bias voltage, V_a, of 0 V and −0.5 V, under a 532-nm light source with a normal incident beam diameter (d_{beam}) of ~1 µm. The input incident light was automated to fall on the mesh points dividing up the image captured with a CCD camera, as shown in the optical microscopy (OM) image in Fig. 1(b). The majority of carriers generated by the optical incidence only within the depletion area would contribute dominantly to the drift currents because the built-in electric field only exists in the depletion area. These drift currents detected as the reverse leakage currents, and the current value at this time was mapped as the current value at the mesh node. The horizontal depletion width was then obtained by simply measuring the $W_{h,x}$ on the mapped image. For increased accuracy, the average depletion width ($W_{ave,h,x}$) was defined as the depletion area divided by channel width L. For the calculation of N_d, the dielectric constant of MoS_2 was assumed to be ~3 at a V_a of ≤0 V [6,7].

Table 1
Horizontal depletion widths, areas, and carrier densities at $V_a = 0$ V and −0.5 V. A_{wd} was calculated with Jimage software [9]. $W_{h,x}$ was obtained from dividing the A_{wd} by the electrode length ($L \approx 12.8\mu$m).

V_a [V]	$W_{h,x}$ [µm]	$W_{ave,h,x}$ [µm]	A_{wd} [µm^2]	N_d [cm^3]	N_{2d} [cm^2]
0	1.84	1.84	23.54	1.57×10^{19}	3.14×10^{13}
−0.5	2.96	2.98	38.14	1.55×10^{19}	3.11×10^{13}
Ratio	1.61	1.62	1.62	0.99	0.99

The *I-V* curve of the Pt/MoS_2 Schottky diode is presented in Fig. 1(c), and the plot of log(dI/dV) vs voltage is given in Fig. 1(d). Assuming the relationship in Eq. (5):

$$I = \sigma V^{\beta} \quad (5)$$

where σ is the conductivity, the ohmic transport behavior starts when $\beta = 1$ [8], and the voltage at this moment is selected as the horizontal turn-on voltage, $V_{turn\text{-}on}$ shown in Fig. 2(a).

Results and discussion

The photocurrent mapping area is indicated by the red box in Fig. 1 (b) and occupies the entire frame in Fig. 2(b). The photocurrent maps obtained at V_a = 0 V and −0.5 V are presented in Fig. 2(c) and (d), respectively, normalized to 100% with the maximum reverse leakage current value at V_a = 0 V. Here, the horizontal depletion area appears symmetrically around the Pt metal as expected when V_a = 0 V, and expands in the x-direction (i.e., the dominant lateral transport direction) with increasing V_a. The depletion width and area values within the

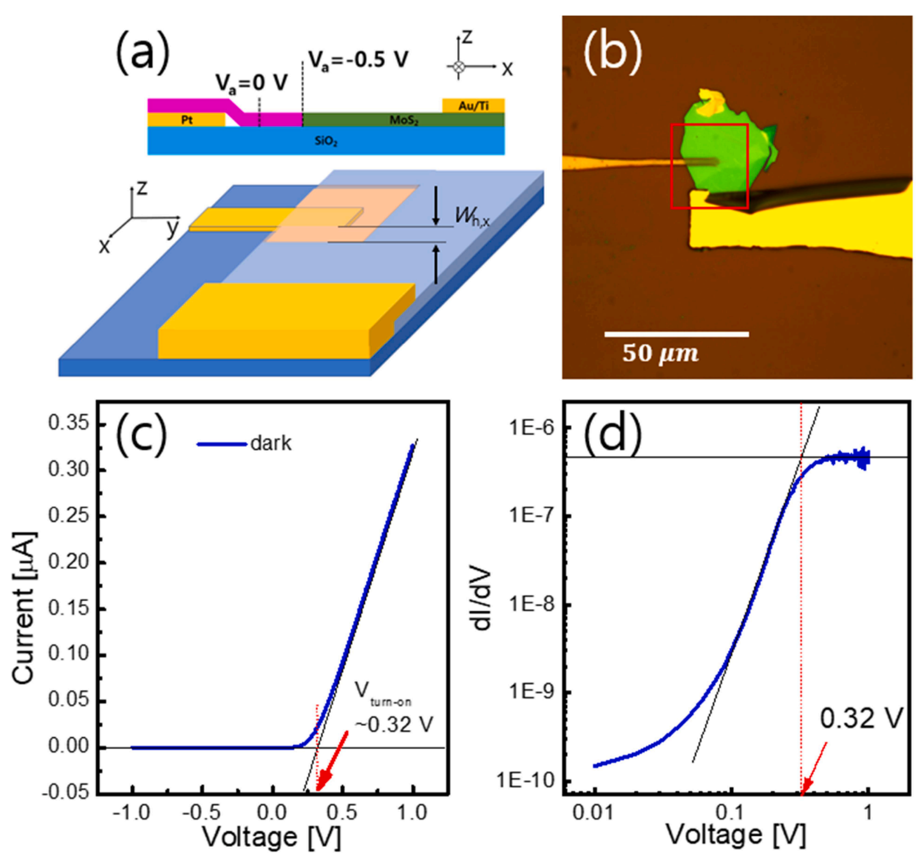

Fig. 1. (a) Schematic diagrams of the 2D Schottky diode, where the depletion width, $W_{h,x}$, varies with V_a. (b) An OM image of the Pt/MoS_2 Schottky diode, with the photocurrent mapping area indicated by the red box. (c) The *I-V* curve of the Pt/MoS_2 Schottky diode. (d) The plot of log(dI/dV) vs voltage, indicating the onset of ohmic behavior. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

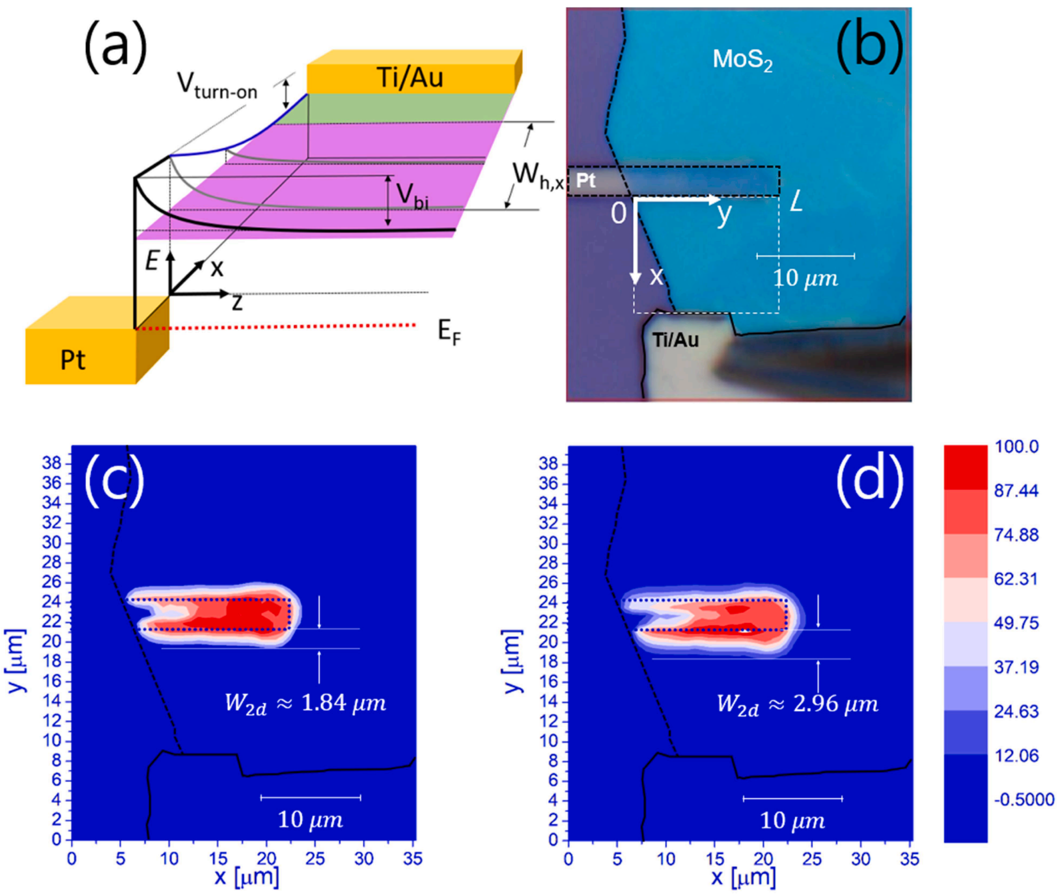

Fig. 2. (a) Schematic energy band diagram. (b) OM image of the photocurrent mapping area corresponding to the red box in Fig. 1 (b). (c and d) Normalized photocurrent maps at $V_a = 0$ V (c) and $V_a = -0.5$ V (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

white box in Fig. 2(b) are summarized in Table 1. The results also demonstrate that the depletion width, $W_{h,x}$, and depletion area, A_{wd}, are both increased by ~1.6 times as the V_a is increased, and the extracted N_d values at each V_a are also in good agreement with each other (i.e., 98.8%). The estimated N_{2d} ($=tN_d$) value of the MoS_2 flake at room temperature is $\sim 3.1 \times 10^{13}$ cm^{-2}, which is a similar order of magnitude to the previously-reported Hall measurement data [1].

Rigorously, in our measurement method, the diffusion current near the boundary between the depletion and neutral regions should be considered. In general, when the *electron-hole* pairs are generated in the neutral region near the depletion boundary, the hole, the minority carriers, overcame into the depletion region can create the diffusion current. But, in our analysis, we assumed and excluded the weak diffusion currents because we estimated that the $W_{h,x}$ error is under the hole diffusion length, which is shorter than the electron diffusion length (~300 nm) [10].

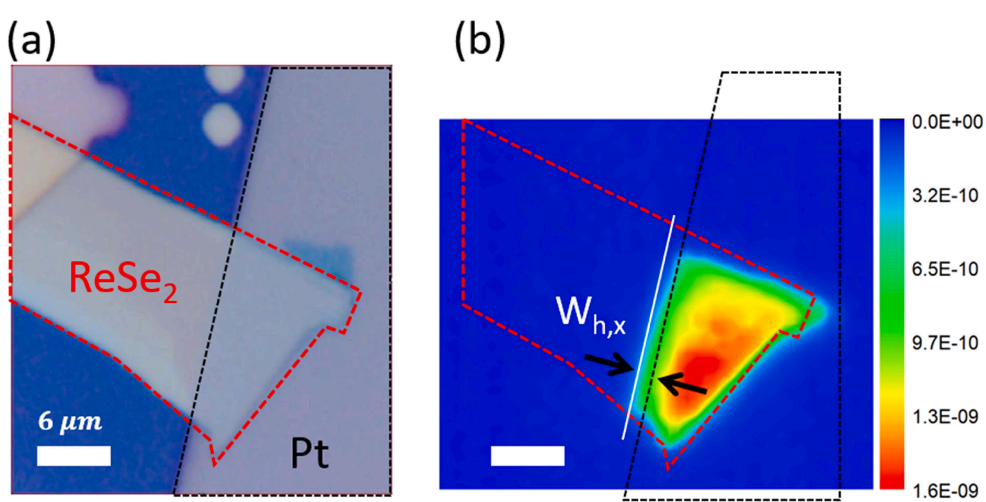

Fig. 3. (a) OM image of the Pt/$ReSe_2$ Schottky diode. (b) Photocurrent map at $V_a = 0$ V.

In order to verify our method, we employed a p-type $ReSe_2$ flake as another example. Fig. 3(a) and (b) shows the OM image and photocurrent map of a lateral $Pt/ReSe_2$ Schottky diode, respectively. The effective 2D carrier density of $ReSe_2$ was extracted through the same method as in Pt/MoS_2 analysis, using $W_{h,x} = 1.3$ μm, $t = 10$ nm, and $V_{h,bi} = 3.3$ V. We confirmed the extracted value, $N_{2d} \approx 3 \times 10^{13}$ cm^{-2} is in a similar order of magnitude to the reported value [11]. We suggest more development in this methodology to reach a more accurate evaluation.

Conclusions

In summary, this study has demonstrated that the 2D carrier density, N_{2d}, of a Schottky junction diode can be obtained easily via a simple depletion width formula in which the turn-on voltage is used as the built-in voltage, and the horizontal depletion width of the photocurrent maps are used as the average depletion width. This method is expected to be useful for research into the diverse applications of 2D materials-based devices.

CRediT authorship contribution statement

Il-Ho Ahn: Methodology, Investigation, Funding acquisition, Conceptualization, Writing - original draft. **Jongtae Ahn:** Methodology, Investigation, Writing - original draft (Co-first author). **Do Kyung Hwang:** Supervision. **Deuk Young Kim:** Funding acquisition, Resources, Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Cui X, Lee GH, Kim YD, Arefe G, Huang PY, Lee CH, et al. Multi-terminal transport measurements of MoS_2 using a van der Waals heterostructure device platform. Nat Nanotechnol 2015;10(6):534–40.
[2] Neamen DA. Semiconductor physics and devices. McGraw Hill International; 2011.
[3] Ahn J, Kang JH, Kyhm J, Choi HT, Kim M, Ahn DH, et al. Self-powered visible-invisible multiband detection and imaging achieved using high-performance 2D $MoTe_2/MoS_2$ semi-vertical heterojunction photodiodes. ACS Appl Mater Interfaces 2020;12(9):10858–66.
[4] Nanobase homepage. https://www.nanobase.co.kr/.
[5] Ra HS, Jeong MH, Yoon T, Kim S, Song YJ, Lee JS. Probing the importance of charge balance and noise current in $WSe_2/WS_2/MoS_2$ van der Waals heterojunction phototransistors by selective electrostatic doping. Adv Sci 2020;7(19):2001475.
[6] Belete M, Kataria S, Koch U, Kruth M, Engelhard C, Mayer J, et al. Dielectric properties and ion transport in layered MoS_2 grown by vapor-phase sulfurization for potential applications in nanoelectronics. ACS Appl Nano Mater 2018;1(11):6197–204.
[7] Santos EJG, Kaxiras E. Electrically driven tuning of the dielectric constant in MoS_2 layers. ACS Nano 2013;7(12):10741–6. https://doi.org/10.1021/nn403738b.
[8] Lindström H, Södergren S, Solbrand A, Rensmo H, Hjelm J, Hagfeldt A, et al. Li^+ ion insertion in TiO_2 (Anatase). 2. Voltammetry on nanoporous films. J Phys Chem B 1997;101:7717–22.
[9] ImageJ homepage. https://imagej.nih.gov/ij/download.html.
[10] Kim YC, Nguyen VT, Lee S, Park J-Y, Ahn YH. Evaluation of transport parameters in MoS2/graphene junction devices fabricated by chemical vapor deposition. ACS Appl Mater Interfaces 2018;10:5771–8.
[11] Choi BK, Ulstrup S, Gunasekera SM, Kim J, Lim SY, Moreschini L, et al. Visualizing orbital content of electronic bands in anisotropic 2D semiconducting ReSe2. ACS Nano 2020;14:7880–91.