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Patterning Bi<sub>2</sub>Se<sub>3</sub> single-crystalline thin films on Si(111) substrates using strong oxidizing acids

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Acidic potassium dichromate solutions ( $K_2Cr_2O_7-H_2SO_4$  and  $K_2Cr_2O_7-HCl$ ) are applied for patterning single crystalline Bi<sub>2</sub>Se<sub>3</sub> thin films on Si(111) substrates. In solutions with appropriate component proportions, vertical walls and mesa-shaped structures on the etching profiles of (001) Bi<sub>2</sub>Se<sub>3</sub> films can be achieved. Stoichiometric etching behavior is noted for Bi<sub>2</sub>Se<sub>3</sub> in  $K_2Cr_2O_7-H_2SO_4$  etchant, while incongruently dissolution of Bi<sub>2</sub>Se<sub>3</sub> in  $K_2Cr_2O_7-HCl$  is observed which leaves a Se deficient layer on the etched film surface. The chemical reaction kinetics of Bi<sub>2</sub>Se<sub>3</sub> in the two different etchants are also discussed.

### 1. Introduction

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The layered compound Bi<sub>2</sub>Se<sub>3</sub> has been used for thermoelectric (TE) energy conversion for years.<sup>1,2</sup> After being revealed as a topological insulator (TI), Bi<sub>2</sub>Se<sub>3</sub> has become much more sought-after than ever before.3 Featuring a large bulk band gap  $(\sim 0.3 \text{ eV})$  and simple Dirac-cone shaped surface states, Bi<sub>2</sub>Se<sub>3</sub> is advocated as the most promising TI for room temperature applications.<sup>4,5</sup> Some fingerprints of Bi<sub>2</sub>Se<sub>3</sub> TI surface states have already been detected in electronic transport measurements, such as B-A interference effects,6 anti-localization behaviors,<sup>7</sup> and unique anisotropic magneto-resistance.<sup>8</sup> These findings have promised novel quantum devices of Bi<sub>2</sub>Se<sub>3</sub> beyond its traditional TE applications. Furthermore, high quality Bi<sub>2</sub>Se<sub>3</sub> thin films can be readily grown on substrates such as Si,9-11 GaAs,12 and InP13,14 at rather low temperatures ( $\sim$ 500 K), which sensibly promotes bottom-up on-chip integration of Bi<sub>2</sub>Se<sub>3</sub> devices.

However, as a key step towards device realization, patterning Bi<sub>2</sub>Se<sub>3</sub> thin films is still of challenge. Physical bombardment of argon ions and reactive ion etching offer very little selectivity of the sample material over photoresist and carbonization of photoresist masks due to long term exposure to high energy ion beams may ensue. The complicated operation also hinders the popularity of dry-etch in processing weakly-bonded Bi<sub>2</sub>Se<sub>3</sub>. As compared to dry etching approaches, wet etching is an effective alternative due to its high etching rate, low cost and high selectivity. The etchants with different etching velocity, surface

roughness, and some other characteristics can further be worked out for various purpose. Among etchants ever employed for Bi<sub>2</sub>Se<sub>3</sub> and other chalcogenides, iodine and/or bromine based chemistries promise selective surface etching at limited rate.<sup>15</sup> For fast chemical cutting of bismuth chalcogenides, the most popular wet etchant ever used is aqueous solutions of HNO<sub>3</sub> and HCl mixture (diluted aqua regia).<sup>16–21</sup> However, these highly corrosive solutions could cause a vigorous uncontrollable reaction with Bi<sub>2</sub>Se<sub>3</sub>, resulting in severe edge undercutting. The diluted aqua regia etchants become even detrimental for handling thin films because they either cause pattern disappearance or trigger the delamination of weakly adhering Bi<sub>2</sub>Se<sub>3</sub> films from bottom substrates.<sup>22</sup>

In this work, oxidizing etchants based on  $K_2Cr_2O_7-H_2SO_4$ and  $K_2Cr_2O_7$ -HCl solutions are used for patterning Bi<sub>2</sub>Se<sub>3</sub> thin film electrodes on Si, respectively.  $K_2Cr_2O_7-H_2SO_4$ -HCl ternary system has been verified suitable for using in etching solutions of covalent GaAs and InP wafers before.<sup>23</sup> It's demonstrated that the simpler  $K_2Cr_2O_7-H_2SO_4$  and  $K_2Cr_2O_7$ -HCl binary aqueous solutions can also produce mesa-shaped structures with vertical walls of layered Bi<sub>2</sub>Se<sub>3</sub> thin films in this research. Superior surface morphologies of the etched Bi<sub>2</sub>Se<sub>3</sub> (001) over the unetched ones are obtained in solutions with proper acidities. However, incongruently etching behaviors on the Bi<sub>2</sub>Se<sub>3</sub> surfaces are noted that a Se depletion surface layer is formed on Bi<sub>2</sub>Se<sub>3</sub> etched in the  $K_2Cr_2O_7$ -HCl solutions.

#### Experimental section

Single crystalline  $Bi_2Se_3$  thin films grown on (111)-oriented Si substrates by physical vapor deposition are adopted in this study. Details of thin film growth can be found in our previously published work.<sup>11</sup> The thickness of  $Bi_2Se_3$  films involved in this study is ~300 nm. Photoresist etching mask is made by standard photolithography. About 1 µm thick resist (AZ5214) is

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Etch solution	Proportion	$\left[ \mathrm{H}^{\mathrm{+}}  ight] \left( \mathrm{mol} \ \mathrm{L}^{-1}  ight)$
K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> -HCl	1:1	6
K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> -HCl	1:2	8
K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> -HCl	1:3	9
$K_2Cr_2O_7-H_2SO_4$	1:1	9
$K_2Cr_2O_7-H_2SO_4$	1:2	12
$K_2Cr_2O_7-H_2SO_4$	1:3	13.5

masked on each  $Bi_2Se_3$  film surface by spin coating. After being prebaked for 65 seconds at 100 degree, the samples are exposed to ultraviolet light for 20 seconds. Submicron ultraviolet mask aligner is applied in this step. After removing the unexposed photoresist in developer solution and rinsed in deionized water, patterned samples are obtained. To enhance the adhesion of photoresist, all the samples are post baked for 5 minutes at 110 degree.

The K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl (H<sub>2</sub>SO<sub>4</sub>) etchants are prepared by intermixing 9 v/v% K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> and 48 v/v% HCl (98 v/v% H<sub>2</sub>SO<sub>4</sub>) solutions in volume proportions of 1:1, 1:2, and 1:3 (thereafter denoted by  $1: n \text{ K}_2\text{Cr}_2\text{O}_7\text{-HCl}$  (H<sub>2</sub>SO<sub>4</sub>), n = 1, 2, 3), respectively at room temperature. As in Table 1, the acquired acidities, as represent by H<sup>+</sup> concentration ([H<sup>+</sup>]) in the solutions, are calculated to be 6 mol  $L^{-1}$ , 8 mol  $L^{-1}$ , and 9 mol  $L^{-1}$ for the 1 : 1, 1 : 2, and 1 : 3 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl etchants, respectively. For the 1:1 to 1:3  $K_2Cr_2O_7-H_2SO_4$  etchants,  $[H^+]$  values are  $9~mol~L^{-1},$  12 mol  $L^{-1},$  and 13.5 mol  $L^{-1},$  respectively. The  $Bi_2Se_3$ films are etched in these aqueous acidic solutions for given time and no stirring is carried out to isolate the influence from hydromechanical effect. After etching, the samples are rinsed in acetone until the photoresist can be stripped. To investigate the dissolution of Bi<sub>2</sub>Se<sub>3</sub>, ascertain the character of corresponding reactions and determine limiting stages of the process, various methods are involved in the experiments. The thickness of the etched films is measured by a surface profilometer (Dektak150, Veeco). Optical microscopy (Olympus BX51), atomic force microscopy (AFM), and scanning electron microscopy (SEM) are employed to investigate the surface morphologies of the obtained patterns. Surface structural and compositional details of etched samples are further studied by Raman and electron dispersive spectroscopy (EDX), respectively. The chemical identification and binding energy study of the etched Bi2Se3 films are conducted by X-Ray Photoelectron Spectroscopy (XPS, Omicron).

#### 3. Results and discussion

Fig. 1(a) shows a photograph of a  $Bi_2Se_3$  film etched by using 1:2  $K_2Cr_2O_7$ –HCl solution. A grid pattern of  $Bi_2Se_3$  with designed 8 µm line width and 50 × 50 µm<sup>2</sup> windows is left on the Si substrate after thoroughly etching. Fig. 1(b) exhibits Raman curves taken from the  $Bi_2Se_3$  grid and the etched window area of the sample, respectively. Three strong peaks locating at 71 cm<sup>-1</sup>, 131 cm<sup>-1</sup> and 173 cm<sup>-1</sup> are attributed to the  $A_{1g}^1$ ,  $E_g^2$ , and  $A_{1g}^2$  transitions of pure  $Bi_2Se_3$  respectively,<sup>24,25</sup>





Fig. 1 (a) An optical photograph of a  $1:2 \text{ K}_2\text{Cr}_2\text{O}_7$ -HCl solution etched Bi<sub>2</sub>Se<sub>3</sub> film with rectangular grid pattern. (b) Raman curves taken from the grid line (red) and window region (black) on (a), respectively. (c) Cross-sectional SEM image indicates the side-wall structure of the etched Bi<sub>2</sub>Se<sub>3</sub> film in (a).

which indicates a good crystallinity of the un-etched part of  $Bi_2Se_3$  film. While there are only two peaks of Si(111) (299.4 cm<sup>-1</sup> and 520 cm<sup>-1</sup>) found on the Raman spectrum from the etched area, indicating a complete removal of  $Bi_2Se_3$  without any deposits left on the Si substrate after chemical reaction. A cross-sectional SEM image of the etched  $Bi_2Se_3$  pattern further manifests the details at the edge of the etched  $Bi_2Se_3$  film. As shown in Fig. 1(c), the side wall of the etched groove is straight and perpendicular to the horizontal surface of  $Bi_2Se_3$  film which unambiguously depicts the superiority of the acid  $K_2Cr_2O_7$  solution in obtaining mesa-shape microstructures of  $Bi_2Se_3$ .

For better describing the dissolving properties of Bi<sub>2</sub>Se<sub>3</sub> in acid  $K_2Cr_2O_7$  solutions, the etching depths ( $\theta$ ) of the Bi<sub>2</sub>Se<sub>3</sub> film are measured at different time intervals (t). A typical  $\theta$ -t curve of  $Bi_2Se_3$  in 1 : 2  $K_2Cr_2O_7$ -HCl etchant is shown in Fig. 2(a), and a constant etching rate of  $\sim$ 120 nm min<sup>-1</sup> is calculated from its linear fitting, indicating a rate-controlled etching reaction. It must be pointed out that the etching almost ceases at depth of 350 nm which is possibly due to the consumption of  $[H^+]$  in the solution. Also noted from the  $\theta$ -t curve is the reaction delay of Bi<sub>2</sub>Se<sub>3</sub> during the initial 15 seconds before the balanced etching rate can be reached. Such behavior is also observed in all other reactions. By carefully excluding any extrinsic contamination on sample surfaces, we suppose the initial dissolving of Bi<sub>2</sub>Se<sub>3</sub> is hindered by a thick native oxidized layer formed on each sample surface which has suffered long-time exposure in air. The induction period varies a lot for different Bi2Se3 samples, despite of the same acidity and temperature conditions are adopted in those reactions, which is ascribed to the reaction dependence on different chemical compositions and/or thicknesses of the oxidized layers on Bi2Se3 samples, and would not be discussed here. After the induction period, the reaction accelerates and the dissolving process of Bi<sub>2</sub>Se<sub>3</sub> exhibits clear dependence on both the reaction temperatures and acidities of the etchants. Fig. 2(b) shows the quantitative Bi<sub>2</sub>Se<sub>3</sub> etching rate dependence on acidities of K2Cr2O7-HCl and temperatures (20 °C to 45 °C). In the  $[H^+]$ : 6 mol  $L^{-1}$  etchant, the chemical reaction is weak that rather slight dissolution of the film can be detected even after the solution temperature is elevated from 20 °C to 45 °C (actually, the etching rate is only increased from



**Fig. 2** (a) Time-dependent etching depth evolution of  $Bi_2Se_3$  in 1 : 2  $K_2Cr_2O_7$ -HCl solution. (b) Temperature-dependent etching rates of  $Bi_2Se_3$  in 1 : 1, 1 : 2, and 1 : 3  $K_2Cr_2O_7$ -HCl solutions, respectively. Inset in (b) is a typical optical microscopic picture taken from a  $Bi_2Se_3$  film with square grid pattern immersed in 1 : 3  $K_2Cr_2O_7$ -HCl for 5 seconds. The arrow indicates an over-eroded site on the pattern.

10 nm min<sup>-1</sup> to a few tens of nanometers per minute as temperature ramps up from 20 °C to 45 °C). While after the  $[H^+]$ of the  $K_2Cr_2O_7$  etchants is increased larger than 8 mol L<sup>-1</sup>, the chemical reaction is obviously activated and the etching rates vield rapid increase at elevated temperatures. As judged from the measured rate curves depicted in Fig. 2(b), the dissolution of  $Bi_2Se_3$  in 1 : 3 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl is nearly three times faster than it in 1:2 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl etchant at room temperature. To quantitatively describe the chemical reaction intensity of Bi<sub>2</sub>Se<sub>3</sub> in the oxidizing acids with different  $[H^+]$ , we calculate the activation energies of etching reactions of  $Bi_2Se_3$  in 1 : 1, 1 : 2, and 1 : 3  $K_2Cr_2O_7$ -HCl solutions (the corresponding [H<sup>+</sup>] is 6 mol L<sup>-1</sup>, 8 mol  $L^{-1}$ , and 9 mol  $L^{-1}$ , respectively) from the plots using Arrhenius equation for these curves shown in Fig. 2(b), and the calculated activation energies are 0.88 eV, 0.74 eV, and 0.47 eV, respectively. It thus strongly manifests that the chemical reaction barrier of Bi<sub>2</sub>Se<sub>3</sub> in the oxidizing acids decreases dramatically as the acidity increases in the etching solutions. However, such an intense reaction leads to severely uneven etching of the patterned film. As shown in inset of Fig. 2(b) is an optical microscopic picture of slightly etched  $Bi_2Se_3$  by 1 : 3  $K_2Cr_2O_7$ -

HCl solution at room temperature, on which it can be clearly figured out that the areas near the grid corners are attacked much faster than the other regions. As the etching proceeds, undesired "W"-shape depth profiles of the film gradually evolve and part of the Bi<sub>2</sub>Se<sub>3</sub> grid pattern gets eventually dissolved.

Almost the same etching behaviors of Bi<sub>2</sub>Se<sub>3</sub> in K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>- $H_2SO_4$  etchants are observed. The 1 : 2 in  $K_2Cr_2O_7-H_2SO_4$  ([H<sup>+</sup>]: 12 mol  $L^{-1}$ ) etchant also yields the same etching rate of  $\sim$ 120 nm min<sup>-1</sup> as obtained in the 1 : 2 in K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl and can produce "U" shape etching profiles of the Bi<sub>2</sub>Se<sub>3</sub> films. Anyway, the electronic characteristics of electrodes and heterojunctions based on the etched Bi<sub>2</sub>Se<sub>3</sub> subject on the microscopic surface properties, it's therefore necessary to analyze the morphologies and stoichiometry of the Bi2Se3 surfaces etched by these two kinds of etchants. As illustrated in Fig. 3(a) is a SEM image of an as-deposited Bi<sub>2</sub>Se<sub>3</sub> thin film. High dense growth spirals surrounded by straight steps are observed in the as-grown Bi<sub>2</sub>Se<sub>3</sub> thin films (highlighted by dashed triangles in Fig. 3(a)). As measured by AFM, the root mean square (RMS) roughness of such surface is  $\sim$ 3 nm (in area of 5  $\times$  5  $\mu$ m<sup>2</sup>), as shown in Table 2. After being immersed in  $1: 2 K_2 Cr_2 O_7 - H_2 SO_4$  solution for 30



Fig. 3 SEM images of an as-deposited  $Bi_2Se_3$  surface (a) and  $Bi_2Se_3$  surfaces etched in 1 : 2  $K_2Cr_2O_7-H_2SO_4$  etchant (b) and 1 : 2  $K_2Cr_2O_7-HCl$  etchant (c), respectively.

Sample surface	RMS roughness	Se : Bi mole ratio
Un-etched Bi <sub>2</sub> Se <sub>3</sub> thin film	3 nm	1.6
In 1 : 2 $K_2Cr_2O_7$ – $H_2SO_4$ solution for 30 s	2.5 nm	1.6
In $1 : 2 \text{ K}_2\text{Cr}_2\text{O}_7\text{-HCl}$ solution for 30 s	1.5 nm	1.1

seconds which corresponds to an etching depth of  ${\sim}60$  nm, these pyramid morphologies completely vanish and a surface decorated with large amounts of irregular-shaped islands sized from  $\sim 20$  nm to  $\sim 300$  nm comes out as exhibited in Fig. 3(b). The surface morphology does not improve too much (RMS roughness  $\sim 2.5$  nm) as compared to the as-deposited Bi<sub>2</sub>Se<sub>3</sub> film. On such etched surface, a Se : Bi mole ratio of  $\sim$ 1.60 is detected by EDX measurement. The Se : Bi mole ratio doesn't change significantly after a further 30 seconds etching period indicates a stoichiometric dissolution of Bi<sub>2</sub>Se<sub>3</sub> in the 1:2 in K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> etchant. Fig. 3(c) shows a SEM image taken from a  $Bi_2Se_3$  film etched in 1 : 2 in  $K_2Cr_2O_7$ -HCl solution at  $\sim$ 60 nm depth too. A much smoother surface (RMS roughness  $\sim$ 1.5 nm) is obtained for Bi<sub>2</sub>Se<sub>3</sub> in this etchant. Not identical to the case of  $Bi_2Se_3$  in 1 : 2 in  $K_2Cr_2O_7$ -H<sub>2</sub>SO<sub>4</sub>, Se : Bi mole ratio on the 1 : 2 in  $K_2Cr_2O_7$ -HCl etched surface is ~1.1 as measured by EDX, implying a Se-dissolving preferred reaction kinetics. As etching proceeds to  $\sim$ 270 nm depth, only Bi signal from the film can be detected by EDX indicating a full depletion of Se. It should be noted that the good epitaxial character with twodimensional surface terrace-step structures of initial Bi2Se3 films disappears after being etched in both solutions, which strongly implies that both etching processes would cause amorphous surface parts of the Bi2Se3 films. It's thus also reasonable to attribute the nano-sized islands with irregular

shapes (as shown in Fig. 3(b) and (c)) to be amorphous  $Bi_2Se_3$  deposits after etching.

It's well known that wet chemical etching proceeds by oxidation of the semiconductor constituents followed by chemical dissolution of the oxides in suitable solvents. For etching covalent chalcogenides such as CdSe, CdTe, and HgCdTe, different dissolving rates between cations and chalcogens are often observed because the hydration of cations is much easier than that of nonfully-oxidized chalcogens on the material surfaces.<sup>26-29</sup> As a result, the etched surfaces of chalcogenides are usually cation-deficient. While no cationdeficient surfaces of etched Bi2Se3 are obtained in our experiments, which suggests quite different reaction kinetics of layered Bi2Se3 as compared to that of covalent chalcogenides in oxidizing acids etchants. To further understand the chemical reaction kinetics of Bi2Se3 in oxidizing acids with different components, XPS study is carried out for characterizing the chemical status of Bi2Se3 surfaces etched in different acid K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> solutions.

As shown in Fig. 4 are core level spectrum of Bi and Se elements detected by XPS from the samples etched in 1:2 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl and 1:2 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> etchants with etching depth of  $\sim$ 60 nm, respectively. The binding energies (BE) obtained in the XPS analysis are standardized for specimen charging using C 1s peak as the reference at 284.8 eV. To precisely determine the peaks' positions, Lorentz-Gauss profiles and Shirley background have been taken for the deconvolution. As indicated in Fig. 4(a) is Bi 4f spectrum from the K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> etched Bi<sub>2</sub>Se<sub>3</sub> sample, in which the intensity contribution for spin-orbit-splitting Bi 4f peaks ( $4f_{7/2}$  and  $4f_{5/2}$ ) from either Bi-O bonding<sup>30,31</sup> or Bi-Se bonding can be clearly distinguished upon deconvolution. The intensities of Bi-O bonding Bi peaks are much stronger than that of Bi-Se bonding Bi peaks, which suggest there exists a bismuth oxide  $(BiO_x)$  thin layer deposited on the Bi<sub>2</sub>Se<sub>3</sub> surface during etching. While for the K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl etched Bi<sub>2</sub>Se<sub>3</sub> case, only a pair of Bi 4f peaks located at 158.82 eV and 164.11 eV are observed which can be



Fig. 4 Bi 4f and Se 3d XPS spectra of Bi<sub>2</sub>Se<sub>3</sub> films after etched by  $1 : 2 K_2Cr_2O_7 - H_2SO_4$  etchant [(a) and (c)] and by  $1 : 2 K_2Cr_2O_7 - HCl$  etchant [(b) and (d)], respectively. Experimental data are the open circles and fits are the solid lines.

precisely attributed to Bi-Se bonding of pure Bi<sub>2</sub>Se<sub>3</sub> (Fig. 4(b)).<sup>32-34</sup> Peaks referred to Se  $3p_{1/2}$  and Se  $3p_{3/2}$  can also be figured out in both fitted XPS spectra as exhibited in Fig. 4(a) and (b), and the broaden peak profiles depict a mixed valence states of Se on both samples.<sup>35</sup> The valence states of Se from  $Bi_2Se_3$  films after etched by  $K_2Cr_2O_7\mathchar`-H_2SO_4$  and  $K_2Cr_2O_7\mathchar`-HCl$ are further investigated by analyzing the peak fitted Se 3d  $(3d_{5/2})$ and  $3d_{3/2}$ ) spectra as illustrated in Fig. 4(c) and (d), respectively. In either Se 3d curve, the pair of high BE component peaks belong to Se-Se bonding of element Se and the other pair are related to Bi-Se bonding, respectively. And no traces of any selenium oxides can be found on the etched Bi<sub>2</sub>Se<sub>3</sub> surfaces in our XPS studies.30 Therefore, it's reasonable to determine that there's only a  $Se^{2-} \rightarrow Se^0$  oxidizing reaction happens for the Se element in both etching processes and the free element Se reactants are deposited onto the Bi<sub>2</sub>Se<sub>3</sub> surfaces. Further, peak intensity contribution from Se-Se bonding dominates in Se 3d spectra of the K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> etched Bi<sub>2</sub>Se<sub>3</sub> sample while it becomes not prominent in K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl etched one, which manifests that there're more Se deposits residual on K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> etched Bi<sub>2</sub>Se<sub>3</sub> surface than those on K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl etched one.

Based on the XPS observations, it should be feasible to determine that the surface chemistry is predominated by bismuth oxides and element Se all through the etching procedure in K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> solutions. Therefore the surface reaction kinetics are only subjected by the rate of reactants reaches and leaves the etched surface.<sup>36</sup> As to our knowledge, there's only tempered chemical reactions happen between bismuth oxides and concentrated acids (such as H<sub>2</sub>SO<sub>4</sub> and HCl) at room temperature. So do them between element Se and concentrated sulphuric acid. As a result, congruently dissolving of Bi and Se will dominate in the etching reaction which is confirmed by our experiment observations.

On the other hand, the valence states of Bi in Bi<sub>2</sub>Se<sub>3</sub> remains intact during etching in K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl solutions. It's thus suggested that the etching action on the Bi<sub>2</sub>Se<sub>3</sub> surface is fully triggered by dissolving of Se. As a result, it leads to the observed incongruently etching behaviors of Bi2Se3 in K2Cr2O7-HCl etchants.

#### 4. Conclusions

To summary, mesa-shaped etching profile of Bi<sub>2</sub>Se<sub>3</sub> is obtained either in 1:2 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl or 1:2 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> aqueous solutions with  $H^+$  concentrations of 8 mol  $L^{-1}$  and 12 mol  $L^{-1}$ , respectively. Dissolving rates of Bi2Se3 are approximately 120 nm min<sup>-1</sup> in both the  $1:2 \text{ K}_2\text{Cr}_2\text{O}_7\text{-H}_2\text{SO}_4$  and 1:2K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl etchants at room temperature. Though either etchant is qualified for preparing desired microscopic patterns of Bi<sub>2</sub>Se<sub>3</sub>, quite distinct dissolving kinetics between these two etchants significantly lead to different reaction products on surfaces of the etched samples. In 1 : 2 K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-H<sub>2</sub>SO<sub>4</sub> etching case, the surface stoichiometry of Bi<sub>2</sub>Se<sub>3</sub> is found intact that the TI surface states would probably being reserved after etching. While the Se-deficient dissolving behavior of Bi<sub>2</sub>Se<sub>3</sub> noted in the K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>-HCl etchants implies surface quality degradation.

Nevertheless, slightly metal-rich surface may benefit a lowresistance ohmic contact formation between Bi<sub>2</sub>Se<sub>3</sub> and electrode metals that has been argued crucial for improving performance of TE devices.37 Considering chemical treatment of semiconductor surfaces is a convenient way to define the surface properties and manufacture micropatterns, our findings may serve as useful reference for fabricating Bi<sub>2</sub>Se<sub>3</sub>-based devices with various purpose.

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