# Effect of surface morphology on the electron mobility of epitaxial graphene grown on 0° and 8° Si-terminated 4H-SiC substrates

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Graphene with different surface morphologies were fabricated on 8°-off-axis and on-axis 4H-SiC(0001) substrates by high-temperature thermal decomposition. Graphene grown on Si-terminated 8°-off-axis 4H-SiC(0001) shows lower Hall mobility than the counterpart of on-axis SiC substrates. The terrace width is not responsible for different electron mobility of graphene grown on different substrates, as the terrace width is much larger than the mean free path of the electrons. The electron mobility of graphene remains unchanged with increasing terrace width on Si-terminated on-axis SiC. The interface scattering and short-range scattering are the main factors affecting the mobility of epitaxial graphene. After the optimization of the growth process, the Hall mobility of the graphene reaches 1770 $cm^2/V{\cdot}s$ at a carrier density of $9.8.\times10^{12}$ $cm^{-2}$. Wafer-size graphene was successfully achieved with an excellent double-layer thickness uniformity of 89.7% on a 3-inch SiC substrate.

**Keywords:** graphene, morphology, Hall mobility, 3-inch SiC substrate

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## 1. Introduction

Graphene is a two-dimensional atomic layer of carbon atoms, forming a honeycomb crystal lattice.[1] The high intrinsic mobility makes it an attractive material for high-speed electronic applications.[2−6] Graphene can be fabricated by means of the exfoliation of bulk graphite,[7,8] chemical-vapor-deposited (CVD) growth on certain metals,[9,10] or epitaxial growth on SiC substrate.[11−14] Graphene formed based on the exfoliation of bulk graphite are discontinuous and unrepeatable, and that fabricated by CVD on metals are polycrystalline. Graphene grown on SiC substrate by high-temperature thermal decomposition offers the advantages of uniform coverage and a coherent structure on wafer scale. Furthermore, graphene grown on HP-SI SiC can be used in situ, without having to be transferred to another insulating substrate.

Graphene should be formed by annealing SiC at high temperatures, either in ultrahigh vacuum or in appropriate gas atmosphere. Silicon atoms desorb from the surface, and the remaining carbon atoms rearrange and rebond to eventually form graphene. The nucleation of carbon atoms is dependent on the SiC surface morphology. Some research groups have investigated the influence of the surface morphology on graphene nucleation.[15−17] Only one group focused on the effect of morphology on Hall mobility, and they mainly study the miscut angles on morphology and Hall mobility.[18]

## 2. Experiment

In this work, graphene with different surface morphology was achieved on the 8°-off-axis and on-axis 4H-SiC substrates in vacuum or argon gas atmosphere at high temperature. Before sublimating, all samples were etched for 30 min at 1600 °C in hydrogen atmosphere. Atomic force microscopy (AFM) was used to study the graphene morphology. The Hall mobility was determined by van der Pauw Hall system. Hall samples were prepared by evaporating Ti/Pt/Au contacts on the top of blanket graphene by lithography. Raman spectroscopy was employed to reveal the graphene quality and layer number.

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## 3. Results and discussion

Figure 1 shows the surface morphologies of epitaxial graphene grown on SiC substrates with different miscut angles. Figures 1(a) and 1(b) correspond to graphene on 8°-off-axis 4H-SiC substrates, while Figs. 1(c)–1(e) correspond to graphene on on-axis 4H-SiC substrates. Wider terraces are observed for graphene on on-axis 4H-SiC compared with 8°-off-axis 4H-SiC. The terrace widths for Figs. 1(a)–1(e) are 0.1, 0.26, 1.25, 4.5, and 5.7 μm, respectively. The 8°-off-axis 4H-SiC substrate has an initial terrace width of ∼0.2 μm, and the terraces of epitaxial graphene grown on 8°-off-axis 4H-SiC are restricted to the initial step of the substrate. However, the restriction is not found on epitaxial graphene grown on on-axis 4H-SiC. Hexagon pits are also clearly observed for graphene on on-axis 4H-SiC in Figs. 1(c)–1(e). It was found that hexagon pits formed during thermal decomposition act as the source of C atoms for graphene growth far from the terrace edge.[19] For 8°-off-axis 4H-SiC substrates, carbon atoms are not required to move far away from the terrace edge due to a large number of terraces, and carbon atoms are prone to nucleate at the terrace edge of SiC substrate.

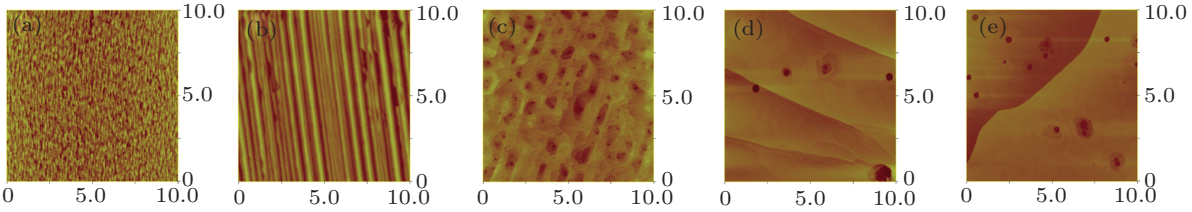



**Fig. 1.** (colour online) Surface morphology of epitaxial graphene (in units of μm) on the SiC substrates with a terrace width of (a) 0.1, (b) 0.26, (c) 1.25, (d) 4.5, and (e) 5.7 μm. (a), (b): on Si-terminated 8°-off-axis 4H-SiC substrates; (c)–(e): on Si-terminated on-axis 4H-SiC substrates.

The terrace width dependence of the Hall mobility and the carrier density of epitaxial graphene grown on 8° and 0° off-axis 4H-SiC substrates are shown in Fig. 2. The hollow squares and circles correspond to graphene grown on 8°-off-axis SiC, while the solid squares and circles correspond to graphene grown on on-axis SiC. The carrier density is fairly similar in the range between $8.8\times10^{12}$ cm$^{-2}$ and $2\times10^{13}$ cm$^{-2}$. The

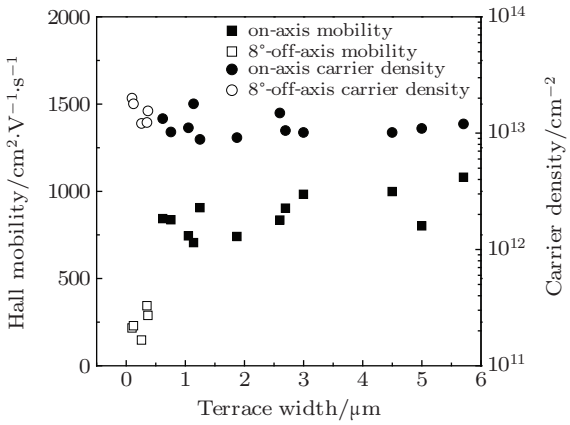



**Fig. 2.** Terrace width dependence of the Hall mobility and the carrier density of epitaxial graphene grown on 8° and 0° off-axis 4H-SiC substrates. The hollow squares and circles correspond to 8° SiC while the solid squares and circles to on-axis SiC.

graphene grown on on-axis SiC shows much higher mobility than those on 8°-off-axis SiC. The mobility tends to saturate with increasing terrace width. This means that the sample shown in Fig. 1(c) with the highest hexagon pit density has almost the same carrier mobility with samples in Figs. 1(d) and 1(e). It seems that the pits have a negligible effect on Hall mobility.

Hall mobility is proportion to the carrier mean free path. The carrier mean free path $L$ can be estimated as follows:[20]

$$L = \frac{3\mu\,(2\pi kTm^*)^{1/2}}{4e}, \tag{1}$$

where $k$ is the Plank constant, $T$ is the temperature, $m^*$ is the effective electron mass, and $\mu$ is the Hall mobility. The effective mass, which is related to the carrier density $n$ and Fermi velocity $v_{\rm F}$, is given by[21]

$$m^* = \frac{\sqrt{\pi n}}{v_{\rm F}}. \tag{2}$$

The carrier mean free path at room temperature was calculated and it was in the range between 2 nm and 20 nm. The terrace width is much larger than the mean free path of the electrons, and it cannot be the main factor responsible for quite different mobilities of graphene grown on different substrates. The value of the carrier mean free path is in good agreement with that derived by Tanabe *et al.*[22] Different scattering

mechanics, including coulomb scattering, short-range scattering, and interface scattering, were considered separately to understand this phenomenon.

First of all, the coulomb scattering can be excluded, as the carrier density of different samples is at the same level. The interface scattering should be absolutely different due to the different substrate miscut angles. The densities of Si/C atoms on the surface of 8° off (0001) toward (11−20) plane SiC substrate and on-axis SiC substrate are different. The interface scattering is one of the reasons for different mobilities. Short-range scattering caused by crystalline disorder and defects of the graphene was considered. Raman spectra are an effective method to study the crystalline disorder and defects of the graphene. Raman spectra of six random samples with different terrace widths are plotted in Fig. 3.

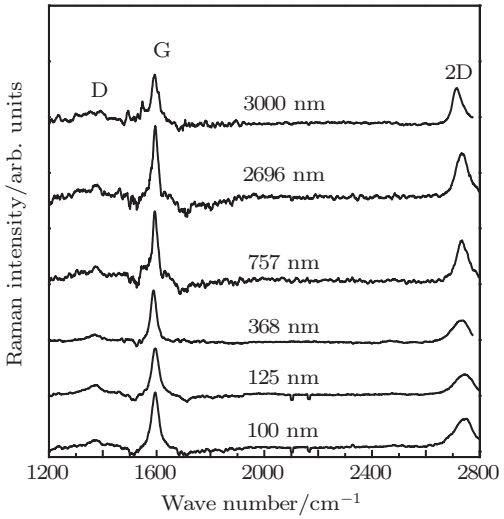



**Fig. 3.** Raman spectra of six random samples with different terrace widths.

The major Raman features of graphene on SiC substrate are the so-called D peak ($\sim$ 1370 cm$^{-1}$), G peak ($\sim$ 1600 cm$^{-1}$), and 2D peak ($\sim$ 2730 cm$^{-1}$).[23] The D peak comes from the crystalline disorder and defects of the graphene. The G peak originates from in-plane vibration of sp$^2$ carbon atoms, and the 2D peak originates from two phonon double resonance. The full width at half maximum (FWHM) of G peak and the intensity ratio of $I_{\rm D}/I_{\rm G}$ can be used to estimate the quality of graphene. Table 1 shows the Raman characteristics of six random samples with different terrace widths. The graphene grown on the substrate with the same miscut angle shows the same disorder and defect level, namely, about 0.3 for 8°-off-axis substrate and 0.2 for on-axis substrate. The graphene grown on 8°-off-axis substrate has larger FMHW of the G peak and $I_{\rm D}/I_{\rm G}$ intensity ratio, which means that the graphene grown on 8°-off-axis substrate has poorer quality. In short, the short-range scattering is also one of the reasons for quite different mobilities.

**Table 1.** Raman characteristics of six random samples with different terrace widths.

| Terrace widths/nm | Carrier density/cm$^{-2}$ | | Hall mobility/cm$^2\cdot$ V$^{-1}\cdot$ s$^{-1}$ | | FWHM of G peak/cm$^{-1}$ | | $I_{\rm D}/I_{\rm G}$ | |
|---|---|---|---|---|---|---|---|---|
| | 8° off-axis | on-axis | 8° off-axis | on-axis | 8° off-axis | on-axis | 8° off-axis | on-axis |
| 100 | $1.992\times10^{13}$ | – | 216 | – | 34.03 | – | 0.31 | – |
| 125 | $1.783\times10^{13}$ | – | 229 | – | 28.57 | – | 0.34 | – |
| 368 | $1.55\times10^{13}$ | – | 288 | – | 24.95 | – | 0.30 | – |
| 757 | – | $1.022\times10^{13}$ | – | 836 | – | 17.98 | – | 0.22 |
| 2696 | – | $1.049\times10^{13}$ | – | 903 | – | 13.83 | – | 0.23 |
| 3000 | – | $1.012\times10^{13}$ | – | 982 | – | 19.25 | – | 0.24 |

To sum up, interface scattering and short-range scattering are responsible for the phenomenon that the mobility on on-axis SiC is much higher than that on 8°-off-axis SiC.

Based on the influence factors of graphene mobility, two-step growth method has been developed for reducing the scattering. The SiC substrate was first heated to a relatively low temperature to form a transition-phase structure, and then heated to target temperature to form a well-ordered graphene. The Hall mobility reaches 1770 cm$^2$/V·s at a carrier density of $9.8\times10^{12}$ cm$^{-2}$. High quality graphene was successfully grown on a 3-inch wafer. The result of the layer number mapping of graphene is shown in Fig. 4(c). The step size was 7.6 mm for $x$ and $y$ directions. Seventy points were tested. Graphenes are primarily double-layer thick, with an excellent uniformity of 89.7%, according to Raman spectra (G/2D peak-intensity ratio of 1). A D/G peak ratio of 0.097 was achieved, which suggests a high quality of the graphene grown on 3-inch SiC.

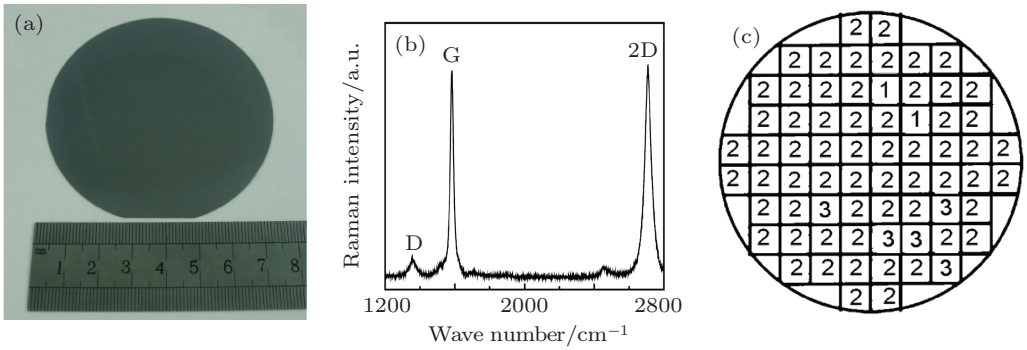



**Fig. 4.** (colour online) (a) Wafer-size graphene grown on SiC substrate up to 75 mm. (b) Raman spectroscopy of graphene. (c) Layer number mapping of a 75-mm wafer-size graphene, illustrating a high uniformity of double layer.

# 4. Conclusion

In conclusion, graphene with different surface morphologies are obtained on the 8°-off-axis and on-axis SiC substrates at high temperature. The graphene grown on on-axis SiC shows higher mobility than those on 8°-off-axis SiC in the same carrier density range. The mobility on on-axis SiC tends to saturate with increasing terrace width. The terrace width is much larger than the mean free path of the electrons, which is not the main reason responsible for quite different mobility of graphene grown on different substrates. Interface scattering and short-range scattering are the main factors responsible for the mobility differences. After the optimization of the graphene growth process and morphology, the Hall mobility reaches 1770 cm$^2$/V·s at a carrier density of $9.8\times10^{12}$ cm$^{-2}$, and 1–3 graphene layers are formed on 3-inch 4H-SiC substrate.

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