Atomically Smooth InSb Quantum Wells on GaAs Substrates

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High-quality InSb quantum wells (QW) are one of the most desirable material systems for the top-down approach in realizing Majorana bound states for topological quantum computing. Such QWs are typically grown with AlInSb metamorphic buffers on GaAs substrates. However, as predicted by the BCF theory [1], high-density pyramid-shaped hillocks form on the surface, which may cause spatial modulation in AlInSb barrier composition as well as variations in InSb QW thickness. Suppression of hillocks is thus essential. Here we report a comparative study on the surface morphology with and without InSb QWs on top of AlInSb metamorphic buffers, as a function of substrate offcut angle.

Modulation-doped InSb/AlInSb QWs were grown on edge-exposed 2” GaAs (001) substrates, using a Veeco Gen10 molecular beam epitaxy (MBE) system (Fig.1(a)). At the wafer centre, a large density of hillocks are formed on the surfaces of both the AlInSb metamorphic buffer and the complete InSb QW structure (Fig.1(b),(d)). Their surface morphologies then transition into smooth regions and eventually become rough again, as the polishing-induced effective offcut increases towards the wafer edge (Fig.1(c),(e)). Formation of hillocks is suppressed for effective substrate offcuts at around 0.4~0.5° towards $[\bar{1}10]$ direction on the AlInSb buffer surface, which coincide with the facet angles of the hillock sidewall at the wafer centre, as derived from AFM scans revealing surface atomic steps. With InSb QW overgrown on the buffer, the large hillocks originated from the AlInSb surface are preserved while small hillocks, due to the very thin InSb QW layer, emerge on the large hillock sidewalls at the wafer centre (Fig.1(d)). The steeper sidewalls of these InSb hillocks indicate a larger substrate offcut needed for their complete suppression, as we predicted recently [2]. Indeed, as shown in Fig.1(e), a new morphological transition region is seen, where large AlInSb hillocks are already suppressed while small InSb hillocks persist. With the growth conditions used, an atomically smooth InSb QW surface is found at substrate offcut angles of around 0.5~0.6°. We propose a model to explain the observed morphological transitions.

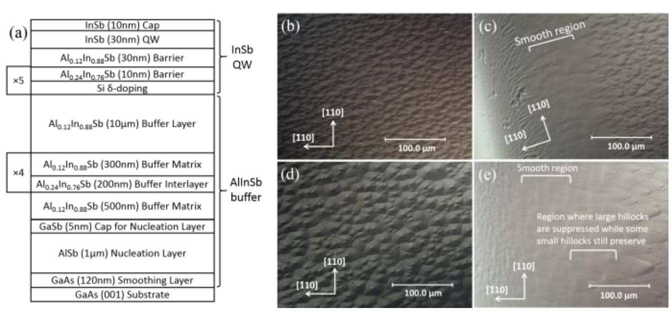

Figure 1. (a) Schematics of the InSb QW structures. (b), (c), (d) and (e) Nomarski images taken at wafer centre and wafer edge on the AlInSb metamorphic buffer surface; wafer centre and wafer edge on the InSb QW surface, respectively.

[1] W. K. Burton, N. Cabrera, and F.C. Frank, Philos. Trans. R. Soc. London **243**, 299 (1951).
[2] Y. Shi, D. Gosselink, K. Gharavi, J. Baugh, and Z. R. Wasilewski, J. Cryst. Growth **477**, 7 (2017).

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Supplementary Information

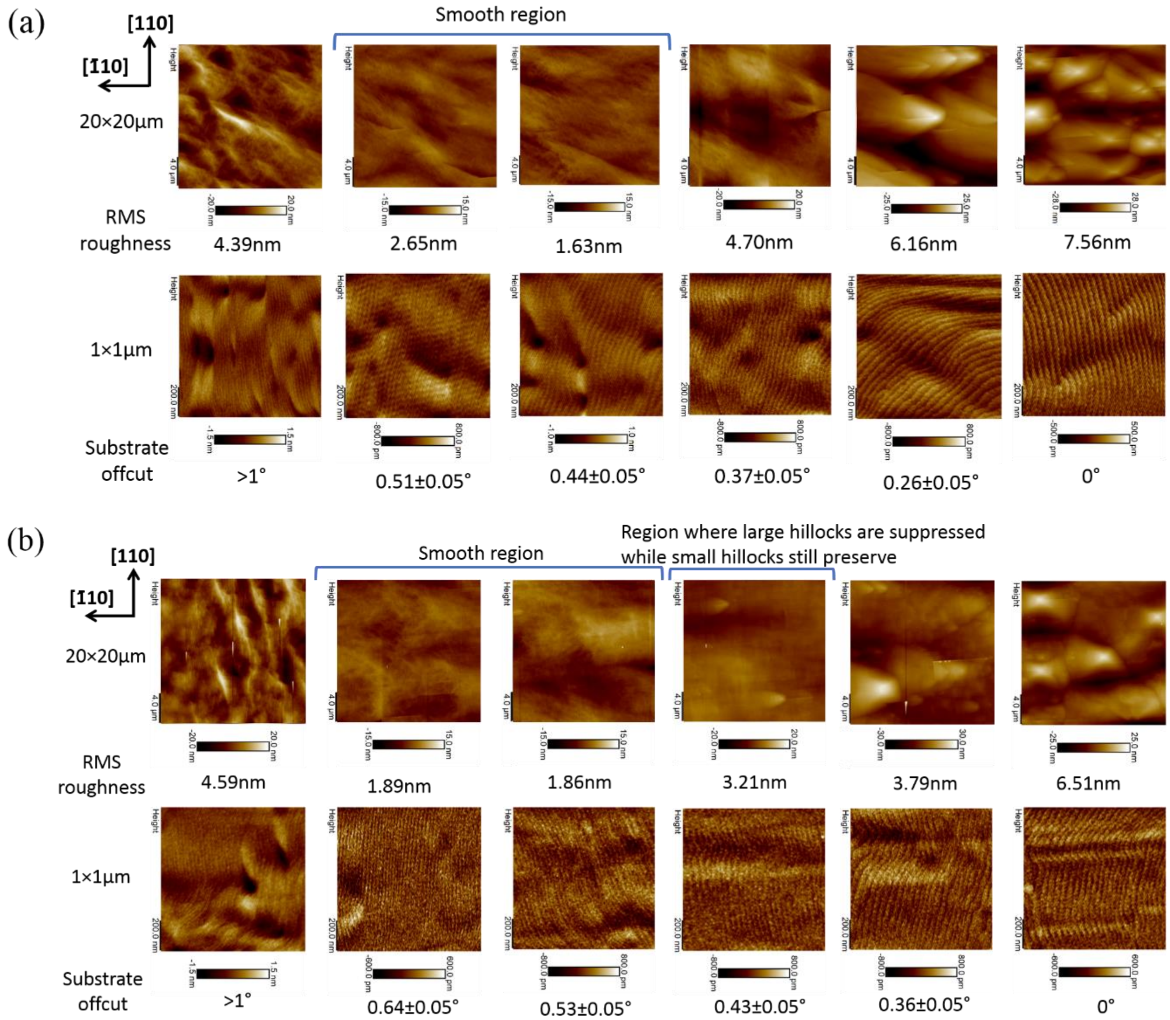

Figure 2. AFM images on (a) the AlInSb metamorphic buffer surface and (b) the InSb QW surface. From right to left, the effective substrate offcut angle increases as moving towards the edge of the wafer in $[\bar{1}10]$ direction. The effective substrate offcut angles are calculated by counting the atomic steps on the surface.

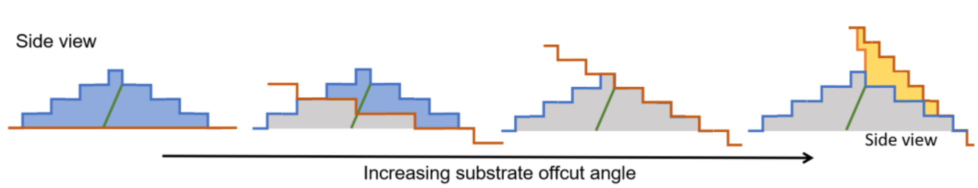

Figure 3. Graphic illustration of the growth mechanism that results in a morphological transition with increasing substrate offcut angle. The red curves are surfaces parallel to the substrate. The green lines represent the threading dislocations. The blue regions are the hillocks formed around the dislocations. The grey and yellow regions are the “suppressed parts” and the “over-suppressed parts” of the hillocks, respectively. Hillock-free and smooth surface is achieved when the substrate offcut angle agrees with the hillock sidewall angle.