Crystalline high aspect ratio nano-pillars generated by ultrafast Bessel beam from sapphire

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Ultrafast lasers deliver high energy density through laser-matter interaction generating extreme pressures and temperatures. The energy deposited in the bulk of transparent materials can lead to the amorphization or re-crystallization of the modified matter [1]. The extreme conditions can even allow the observation of previously unreachable crystalline structures [2].

Recently, by engineering the 100 fs pulse in a first-order Bessel beam, we demonstrated that it is possible to to create positive structures from sapphire bulk in a laser-induced extrusion process [3]. Depending on the local intensity, three regimes could be observed, ranging from very straight pillars (see Fig.1a) to very wavy ones, shaped by surface tension and capillary instability (see Fig.1e). Here, we report Transmission Electron Microscopy (TEM) and EBSD (Electron BackScatter Diffraction) characterizations of the three regimes, allowing a better understanding of the formation mechanisms.

Surprisingly, all structures above the surface are perfect mono-crystals. Detailed crystalline orientation analysis reveals that the very straight pillars are obtained through the translation of a solid rod of sapphire without phase change. In contrast, the wavy pillars are the result of a resolidified ejection of softened/molten material shaped by capillary instabilities, which have further undergone recrystallization.

In Fig. 1, we compare two structures: a straight nano-pillar (Fig.1a) and a near spherical one (Fig.1e) with their associated TEM characterizations. On the left, the TEM analysis reveals the crystalline order of the pillar (Fig.1b,1c) and that its orientation is very close to that of the bulk. Below the sample surface, the TEM analysis shows the plasma formation process and amorphous regions are highly localized with spatial scales as small as 50 nm (Fig.1b,1d). On the right side of Fig.1, the TEM analysis shows the perfect recrystallization of the entire volume of the 1.5 µm sphere (Fig.1f,1g), with a largely different orientation compared to the bulk.

Our study allowed to develop a clearer picture of the nano-pillar formation mechanisms in laser-induced extrusion-like process. This is of interest not only for applications that required specific properties of the pillar, but also to understand the complexity of the processes that follow the laser-matter interaction.

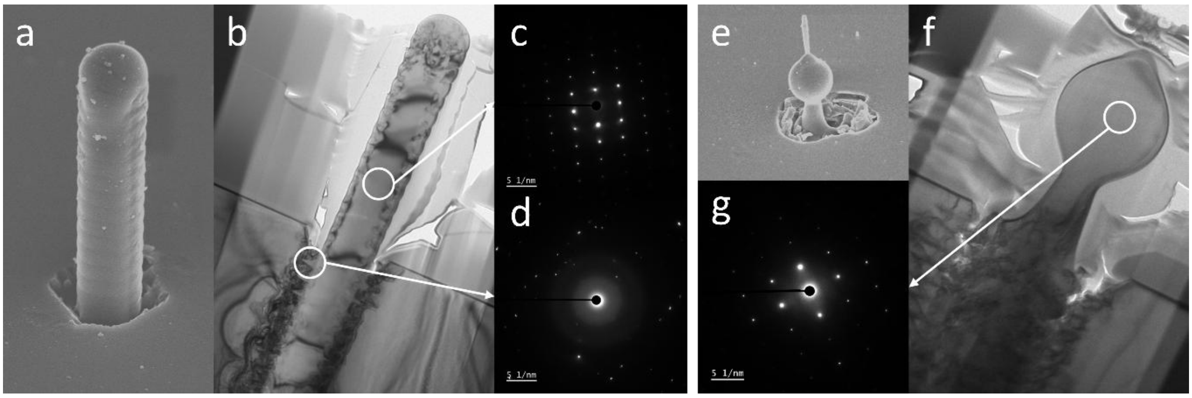

Fig. 1 TEM analysis of sapphire nano-pillars fabricated using a single ultrafast pulse shaped as a Bessel beam. (a, b) SEM and TEM images of a straight pillar with an 800 nm diameter and 4.4 µm height. (c, d) Selected area electron diffraction (SAED) images showing the crystalline structure of the pillar and localized amorphous material, respectively. (e, f) SEM and TEM images of a wavy pillar with a 1.5 µm diameter and 5 µm height. (g) SAED image highlighting the crystal structure of the wavy pillar.

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35-word abstract

An ultrafast first-order Bessel beam can generate high-aspect-ratio nano-pillars on sapphire via material extrusion. Transmission Electron Microscopy analysis reveals that the nano-structures are monocrystals and provides new insights into the mechanisms behind their formation.