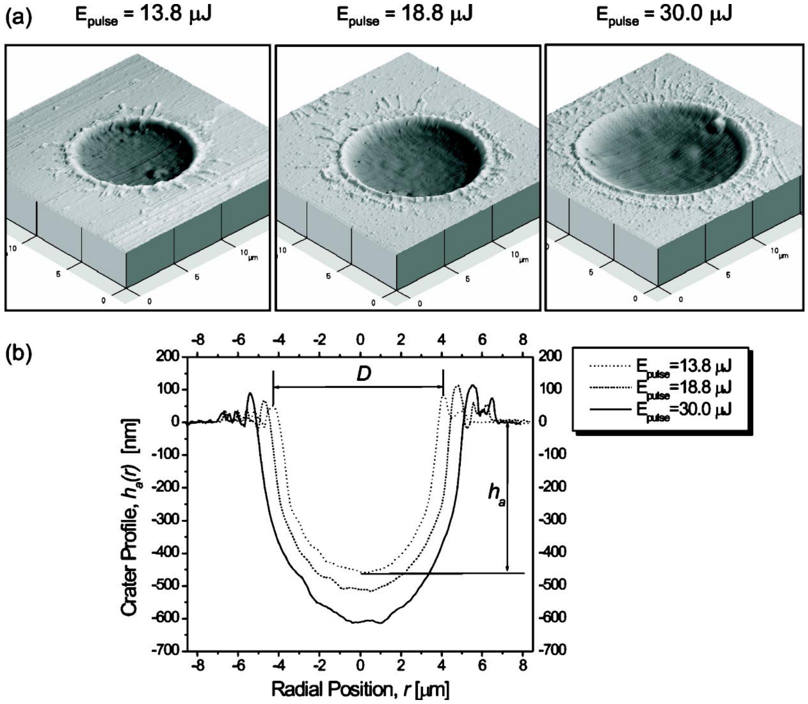

FIG. 1. Quantitative evaluation of single-shot laser ablated craters using an atomic force microscope. (a) Three-dimensional AFM images of single-shot craters ablated in vacuum with three different laser pulse energies, $E_{\text{pulse}}=13.8$, 18.8, and 30.0 μJ corresponding to laser fluences of $F_0^{\text{av}}=13.1$, 17.9, and 28.6 J/cm^2, respectively. The diameter of the craters increases with laser energy. (b) Center-line profiles of the ablated craters. The crater diameter D and the crater depth h_a were measured from data similar to the profiles presented here. The diameter is taken as the distance across the highest points of the rim and the ablation depth is measured from the surface to the bottom of the crater as illustrated in the graph. Note that the scale in the lateral direction is 10 times larger than in the direction normal to the target surface.

A. Single-shot ablation threshold

The "single-shot ablation threshold" $F_{\text{th}}^{N=1}$ represents the minimum average laser fluence required to initiate ablation with the first laser pulse. We determine $F_{\text{th}}^{N=1}$ by measuring the crater diameter D for different average laser fluences F_0^{av} and by using the linear relationship between D^2 and $\ln(F_0^{\text{av}})$ that can be derived as follows.

For a Gaussian spatial beam profile with a $1/e^2$ laser beam radius w_0 the radial distribution of the laser fluence is presented by

$$F(r) = F_0^{\text{peak}}\exp\left(-\frac{2r^2}{w_0^2}\right), \tag{2}$$

where F_0^{peak} is the peak laser fluence. Substituting $r=D/2$ and recognizing that the material cannot be ablated for laser fluences lower than the threshold (namely, $D=0$ at the threshold laser fluence, $F_0^{\text{peak}}=F_{\text{th}}$), we obtain[14]

$$D^2 = 2w_0^2 \ln\left(\frac{F_0^{\text{peak}}}{F_{\text{th}}}\right). \tag{3}$$

The peak laser fluence F_0^{peak} is related to the total pulse energy E_{pulse} according to

$$F_0^{\text{peak}} = \frac{2E_{\text{pulse}}}{\pi w_0^2}, \tag{4}$$

because E_{pulse} is the integrated value of the Gaussian profile of laser fluence over the irradiated area with a radius w_0. In the literature, most studies report the fluence in terms of an average value defined by

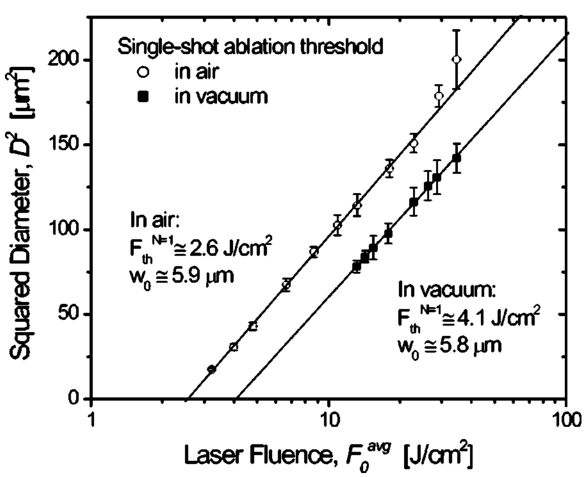

FIG. 2. The single-shot ablation threshold measurements of borosilicate glass with laser pulses of λ=780 nm and τ=200 fs. The squared diameter D^2 of the ablated areas is plotted as a function of the laser fluence F_0^{av}. The slope of the linear fit [Eq. (6)] yields the beam radius at the surface, w_0, and the extrapolation to zero provides the single-shot ablation threshold $F_{\text{th}}^{N=1}$.

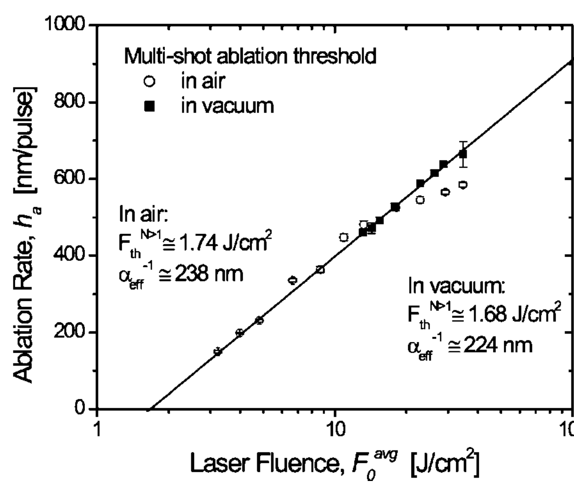

FIG. 3. The multishot ablation threshold measurements of borosilicate glass with laser pulses of λ=780 nm and τ=200 fs. The plots present the logarithmic dependence of the ablation rate h_a on the laser fluence F_0^{av}. The slope of the linear fit [Eq. (10)] can be interpreted as the effective optical penetration depth α_{eff}^{-1}. The extrapolation to zero provides the multishot ablation threshold $F_{\text{th}}^{N>1}$.