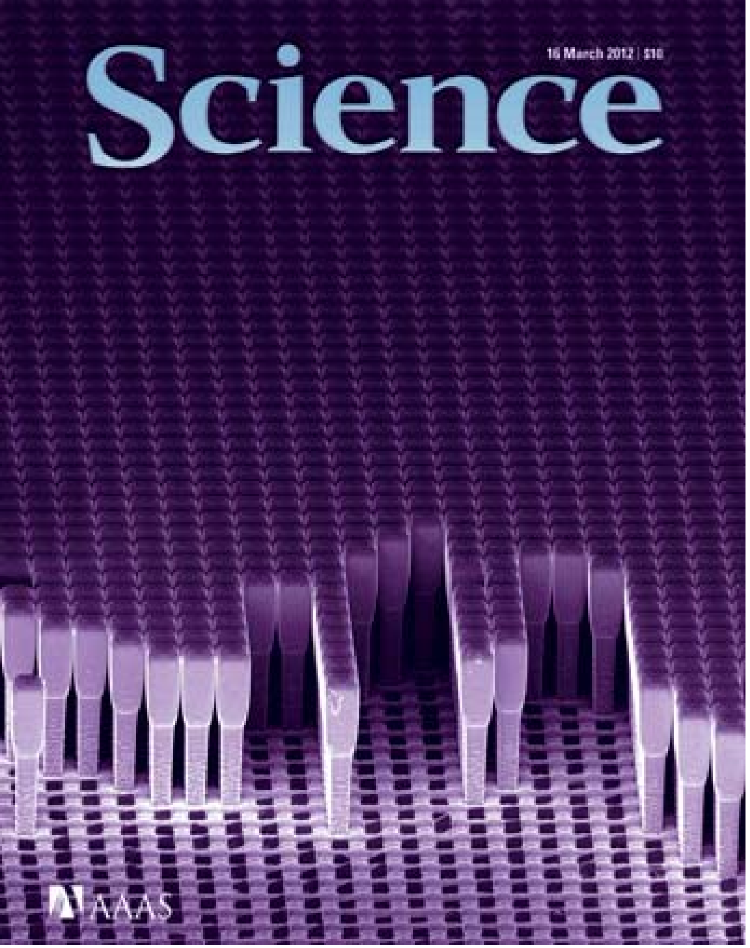

False-colored scanning electron micrograph of ~8-micrometer-tall germanium crystals, separated by finite gaps, grown onto silicon pillars. In structures like this one, wafer bowing and layer cracking are absent, allowing single-crystal integration of different materials onto a silicon substrate, which serves as a platform for many applications, such as multiple-junction solar cells, x-ray and particle detectors, or power electronic devices.

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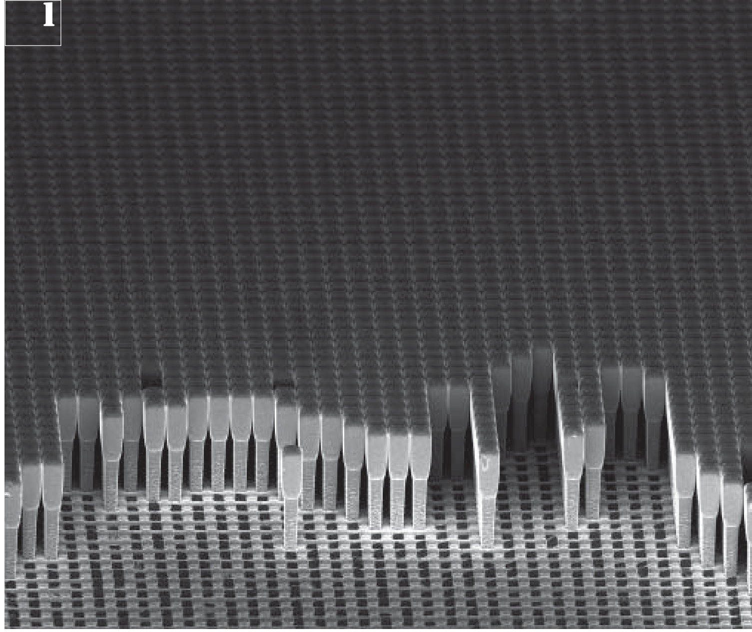
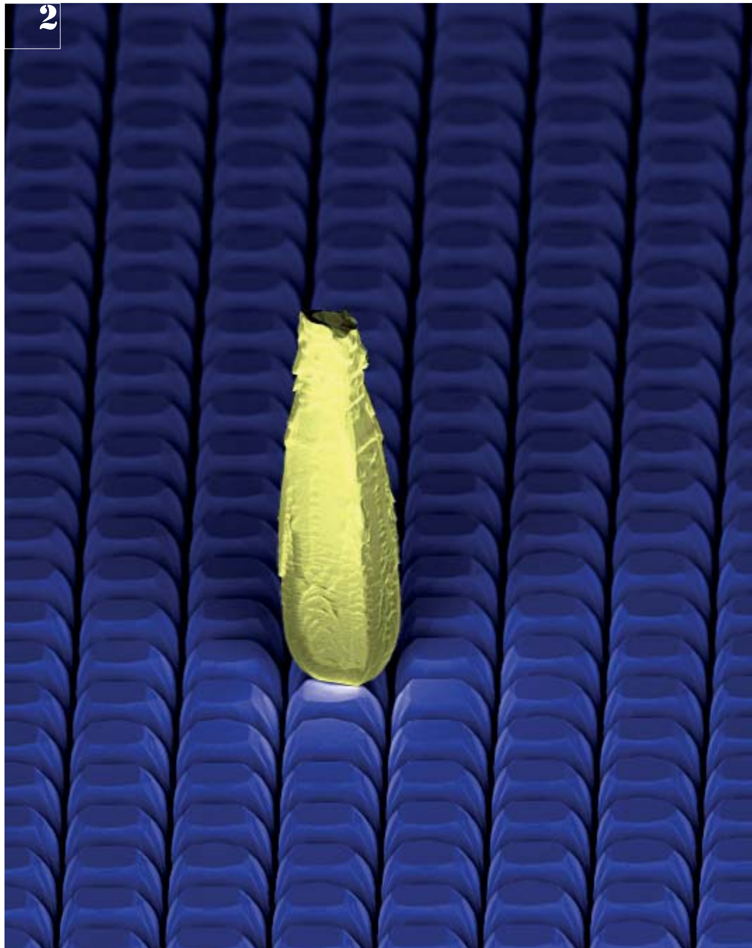
Space-filling three dimensional semiconductor structures

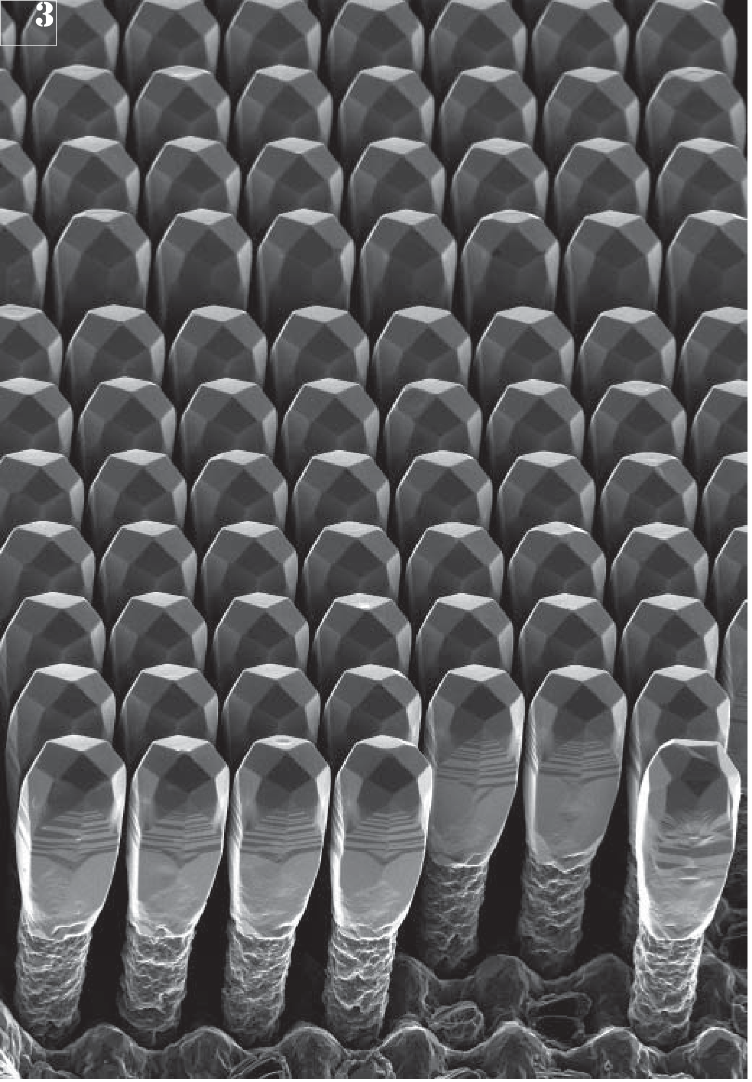
Stacks of epitaxial semiconductor layers form the basis of a wide variety of modern devices such as high electron mobility transistors, high efficiency solar cells and solid state lasers. Many attempts have been made over the past decades to integrate such devices on cheap and abundant silicon substrates, thus adding new functionalities to silicon technology. Combining materials differing in lattice parameter and thermal properties in a monolithic layer stack may, however, lead to crystal defects and often complete device failure. In collaboration with colleagues from the CSEM, the Politecnico di Milano and the Università di Milano Bicocca, we have now developed a new method by which highly perfect, monolithic structures composed of different semiconductors can be manufactured to virtually unlimited thickness, without having to take recourse to state of the art bonding techniques. Thanks to this novel approach, crystal defects, normally present in layers of atoms differing in size, are entirely eliminated. Moreover, disruptive substrate bowing, caused by unequal thermal expansion coefficients of dissimilar materials, is largely absent. Most importantly, fatal layer cracking induced by thermal stresses can no longer occur.



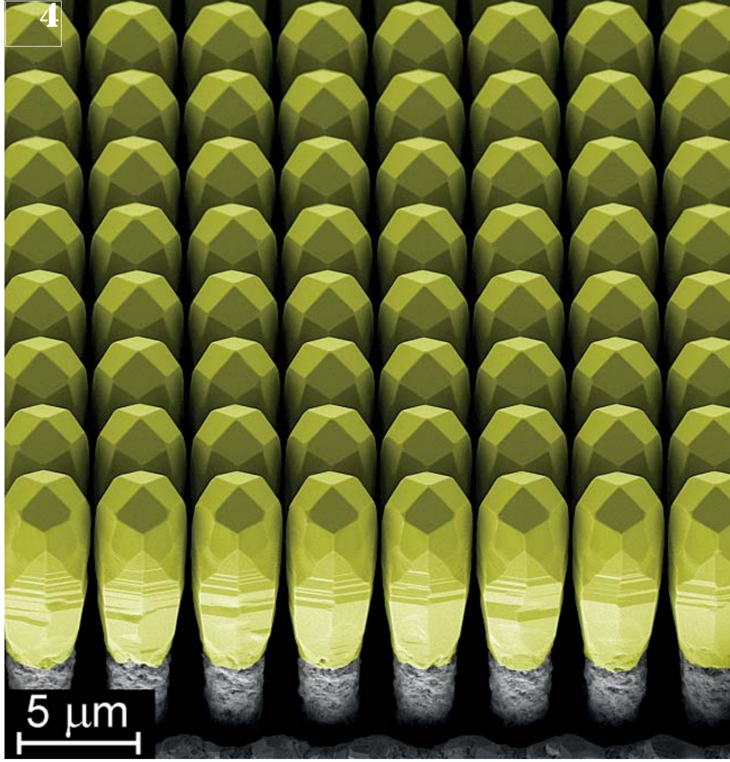
1 Scanning electron micrograph in perspective view of an array of 8 μm tall Ge crystals grown epitaxially on Si pillars. The array was obtained under conditions of self-limited lateral expansion of the crystals, thus preventing the latter to fuse and form a continuous film. In the foreground of the image part of the array was broken during sample processing.



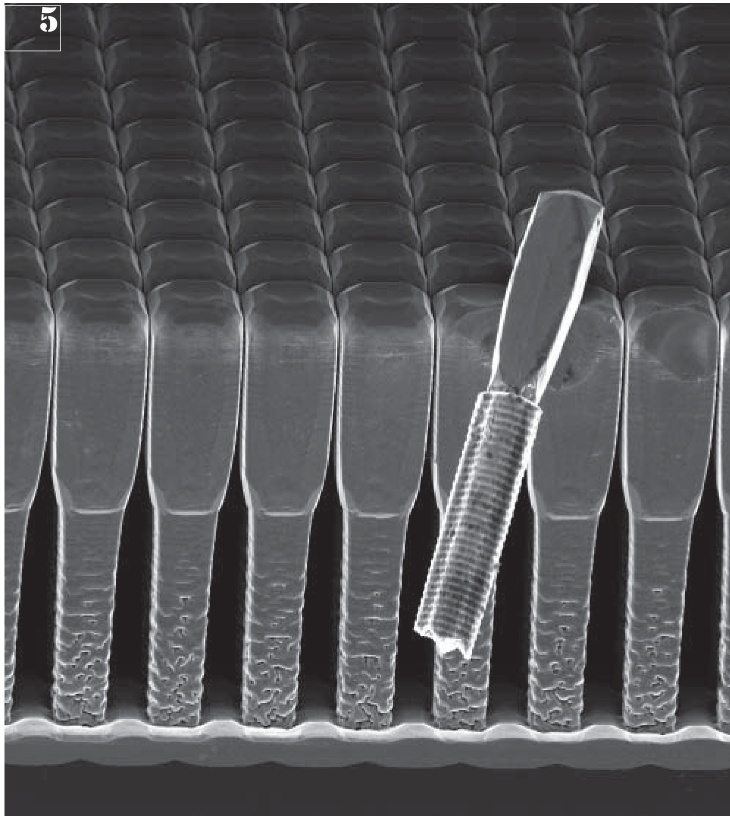
2 Colorized scanning electron micrograph in perspective view of an array of 20 μm tall Ge crystals grown epitaxially on Si pillars. A broken Ge crystal (yellow) rests on the array upside down. The array was obtained under conditions of self-limited lateral expansion of the crystals, thus preventing the latter to fuse and form a continuous film.



3 Scanning electron micrograph in perspective view of 8 µm tall, facetted Ge crystals grown epitaxially on Si pillars. The array was obtained under conditions of self-limited lateral expansion, leaving a small gap between neighboring crystals.



4 Colorized scanning electron micrograph in perspective view of 8 µm tall, facetted Ge crystals grown epitaxially on Si pillars. The array was obtained under conditions of self-limited lateral expansion, leaving a small gap between neighboring crystals.



5 Scanning electron micrograph in perspective view of 8 µm tall Ge crystals grown epitaxially on Si pillars. The array was obtained under conditions of self-limited lateral expansion, limiting the distance between nearest neighbors to about 50 nm, thus preventing crystals to fuse and form a continuous film. A remnant of an etched sample adhered by chance to the first row of crystals. It consists of a Ge crystal on top of a Si pillar exhibiting sidewall ripples formed during deep reactive ion etching of the substrate.

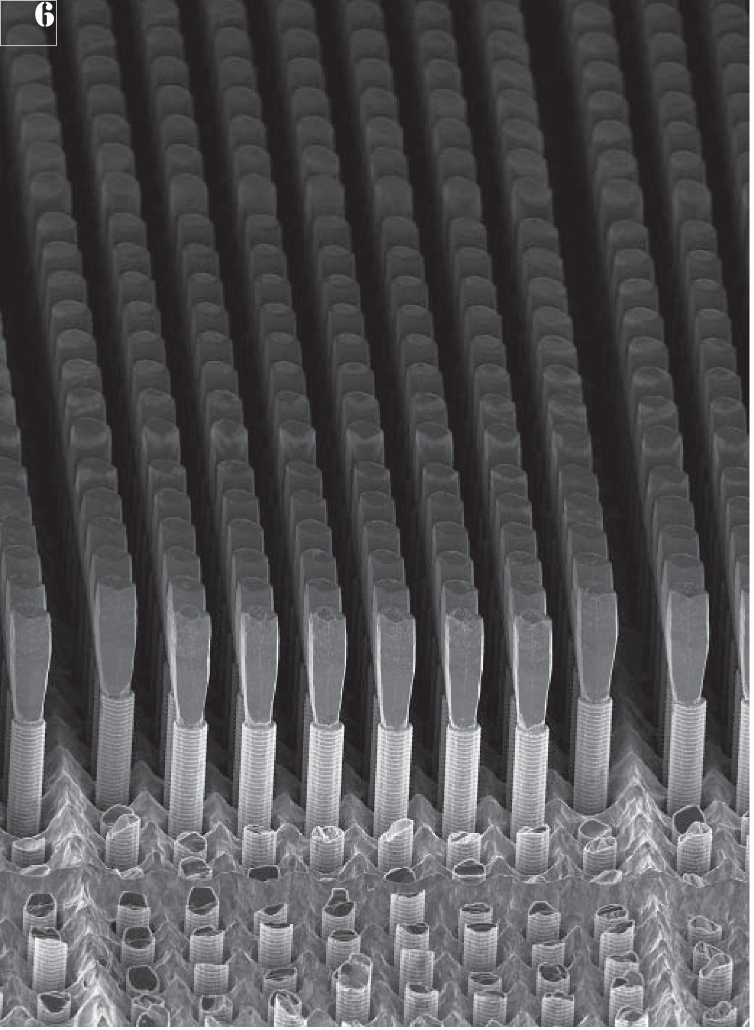
Resembling a chocolate bar

The basic idea leading to this remarkable behavior is very simple. Rather than consisting of continuous layers, the structures are composed of a space-filling array of individual crystals, separated by narrow gaps of several tens of nanometers. They are made in the following way. In a first step a silicon wafer is patterned by photolithography and subsequently etched into a structure resembling a chocolate bar. The depth of the trenches separating the elevated regions typically exceeds their width of a few micrometers. The desired three-dimensional semiconductor structures are then grown onto the substrate pillars under conditions assuring a minimum separation of neighboring crystals. The method has been perfected for defect-free germanium structures on top of silicon wafers, for which a record height of 50 µm was achieved. Based on the know-how gained in the course of this development, we are confident that in the future the new concept will be transferrable to many other material combinations.

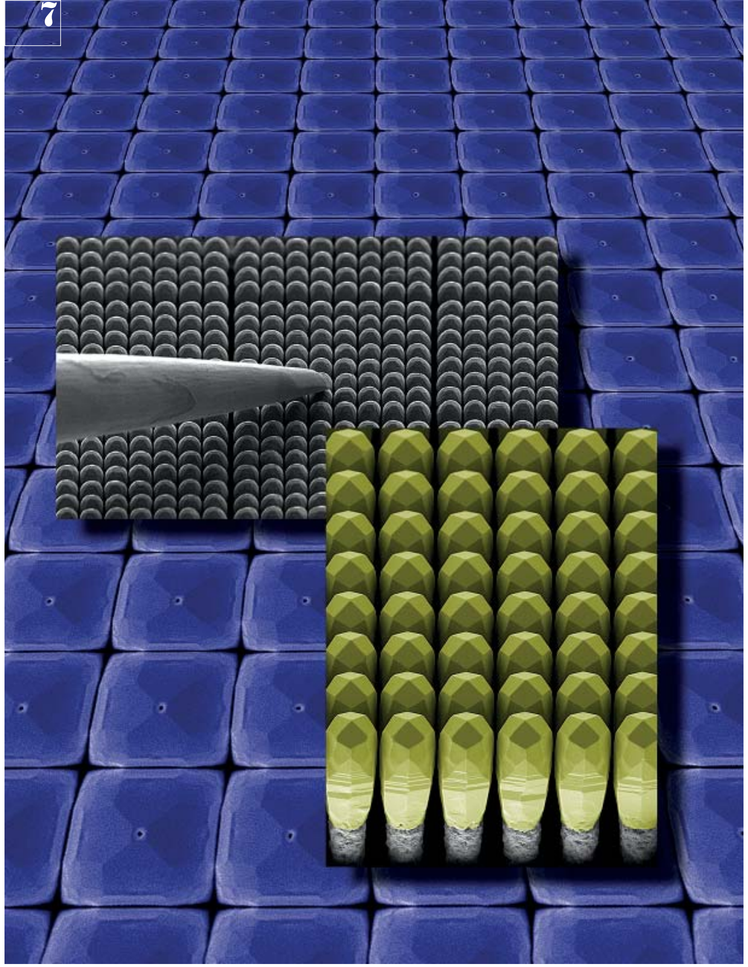
Novel applications in many fields

The ability to synthesize virtually defect-free monolithic semiconductor structures allows for novel applications in many fields. A particularly exciting example is given by energy-resolving X-ray imaging detectors with ultra-high spatial resolution. Here, thick germanium absorbers are ideally suited. They might result in far lower doses necessary for X-ray imaging in medical applications. High efficiency multiple-junction solar cells for concentrator and space applications are another example for which the new method offers substantial cost and weight reductions by replacing expensive, fragile and heavy germanium substrates by cheap and light silicon substrates of high mechanical stability. Another example of potential interest could be power electronic devices grown onto large silicon wafers.

This research work has been generously supported by the Nano-Tera project «NEXRAY» – Next Generation X-ray Systems – one goal of which is the development of novel X-ray imaging detectors.

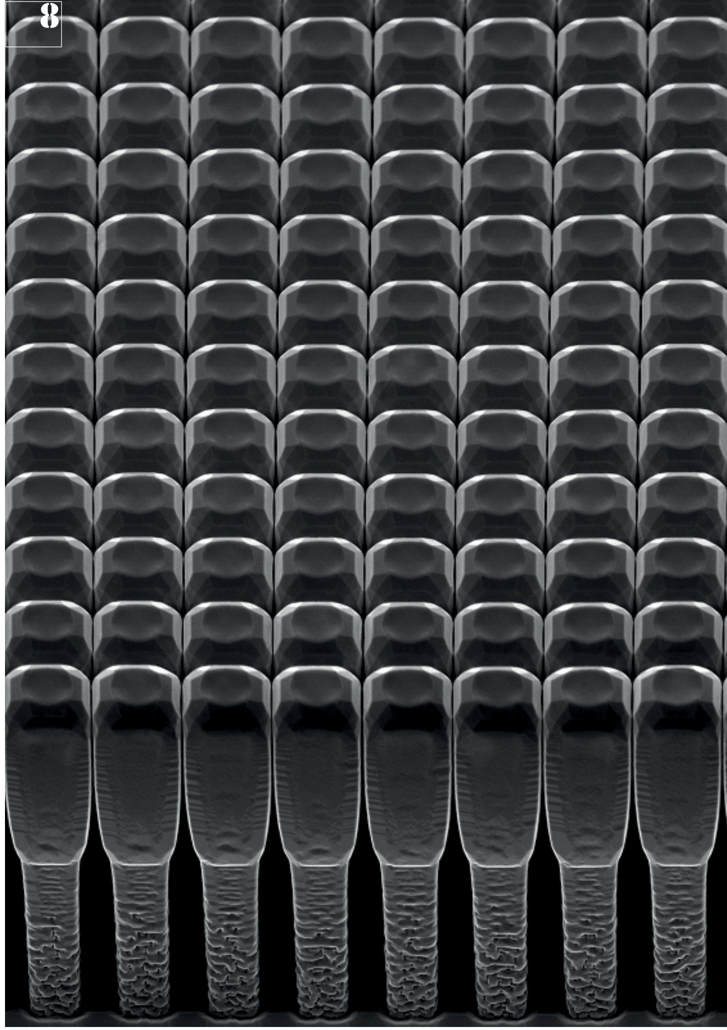


6 Scanning electron micrograph in perspective view of an array of etched, 8 µm tall Ge crystals grown epitaxially on Si pillars. In the foreground of the image part of the array was broken during sample processing.



7 Scanning electron microscopy images in perspective view (yellow and gray scales) of facetted Ge-crystals grown epitaxially on Si pillars. One crystal in the grayscale image is electrically contacted by a Pt-Ir needle with tip radius of ~1 µm. The blue background shows the top surface of a space-filling array of 50 µm tall Ge towers. All structures were obtained under conditions of self-limited lateral expansion, preventing crystals to fuse and form a continuous film.

8 Scanning electron microscopy image in perspective view of 8 µm tall Ge crystals grown epitaxially on Si pillars. Crystal arrays are obtained under conditions of self-limited lateral expansion, limiting the distance between nearest neighbors to about 50 nm, thus preventing crystals to fuse and form a continuous film.



All pictures: C.V. Falub, Laboratory for Solid State Physics

Links:

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