

Manufacturing Gold Nano-Jewellery

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Jewellery is an important feature in the life-style of humans worldwide, but what market for nano-jewellery? A typical element in a necklace is a few millimetres in size compared to a typical human at about two metres in height, so something like a factor of 1000 emerges. If we start from something that is a few tens of nanometres in size, an application of the same ratio suggests we should look for things a few tens of micrometres in size, and what do we find? Bacteria – and there are trillions not just billions of them! So if we can make nano-jewellery that is the right size for bacteria, the potential market is immense.

Recent work reported in an article by us in the journal *Nanotechnology*¹ shows how we can manufacture strings of gold nano-beads encased in a thin transparent filament of glassy silica – just the thing for nano-jewellery and made from gold as well. Products derived from this technology could really take off in the world of microorganisms, unfortunately though they will not greatly enhance the profits of gold mines.

The technology involved is itself quite simple. We start with a crystalline silicon wafer of the sort used in semiconductor devices and deposit on its surface a very thin film of gold. Another bare silicon wafer is then placed at a very small distance above the coated wafer and the whole sandwich heated to a temperature of about 1100 °C for 60 minutes in an atmosphere consisting of nitrogen or argon with about 3 to 5 parts per million of oxygen. The first thing that happens is that the gold film breaks up into tiny drops because of the influence of surface tension and at the same time the oxygen in the surrounding atmosphere attacks the surface of the upper wafer to create a vapour concentration of silicon monoxide SiO. This SiO then dissolves in the gold drops, along with some of the oxygen from the vapour, and the two combine to form silica (SiO₂) molecules. Because silica is not very soluble in gold, it tends to precipitate at the interface

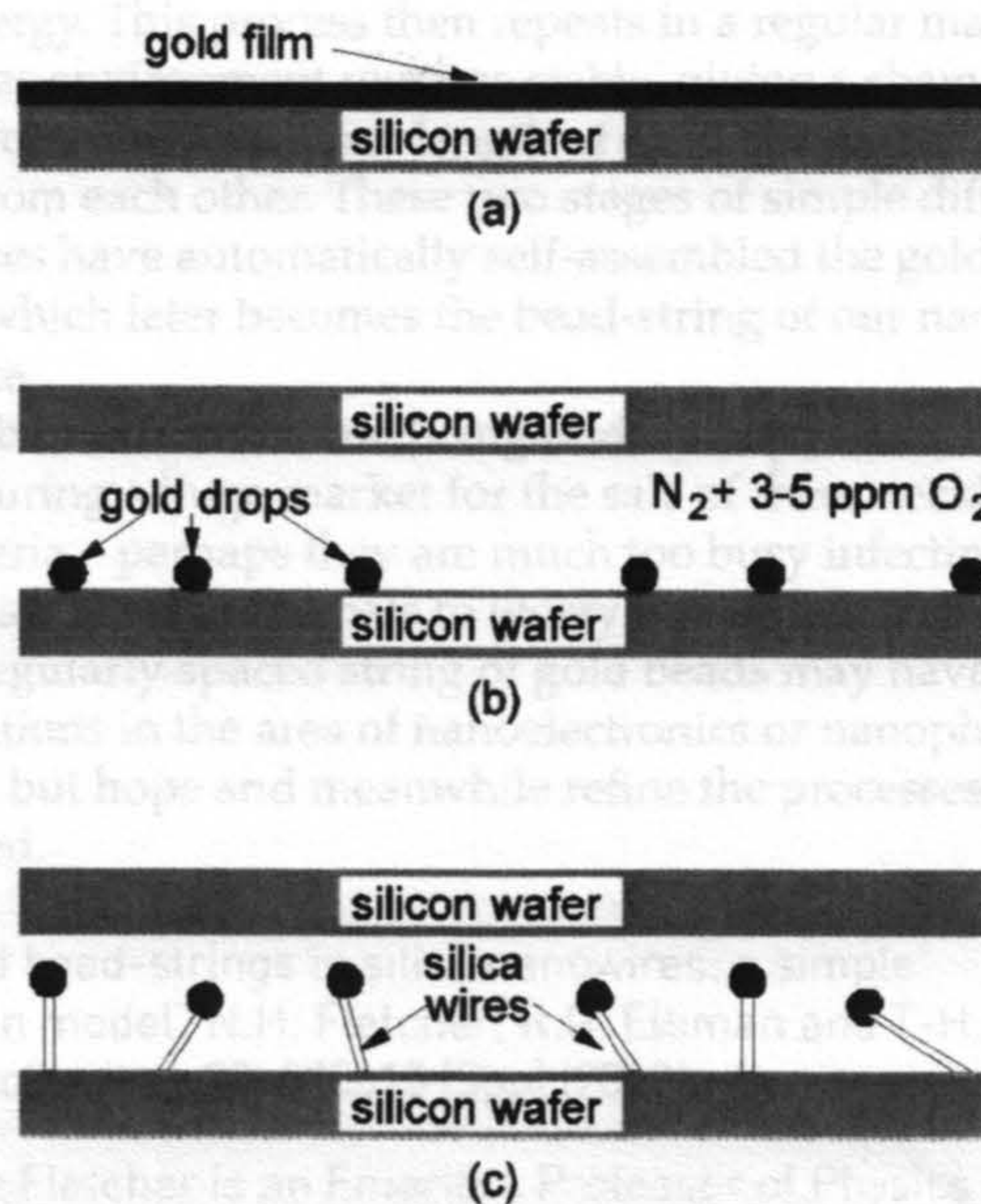


Figure 1. The growth technique described here for silica nanowires: (a) a gold film is deposited onto a silicon wafer; (b) the wafer is capped by another bare wafer and heated in an inert gas atmosphere with 1 to 5 ppm of oxygen and the gold film condenses into a distribution of small gold drops; (c) silica wires grow from the base of the gold drops, bearing them aloft.

between the gold and the silicon substrate and the gold drop is lifted up on a column of amorphous silica. This results in the growth of a population of silica whiskers, or wires as they are often called, each capped with a liquid gold drop which continues the growth process as shown in Figure 1.

So far there is nothing very special about this process, but then something strange happens: in a proportion of the growing wires ranging from 1% to 80% the gold drop begins to leave behind it a trail of small gold droplets with nearly regular spacing, the diameter of each droplet being about one fifth to one half of the wire diameter but more like one tenth of the diameter of the main growth drop at the end of the wire. Examples are shown in Figure 2, some irregularity being introduced by the presence of neighbouring wires.

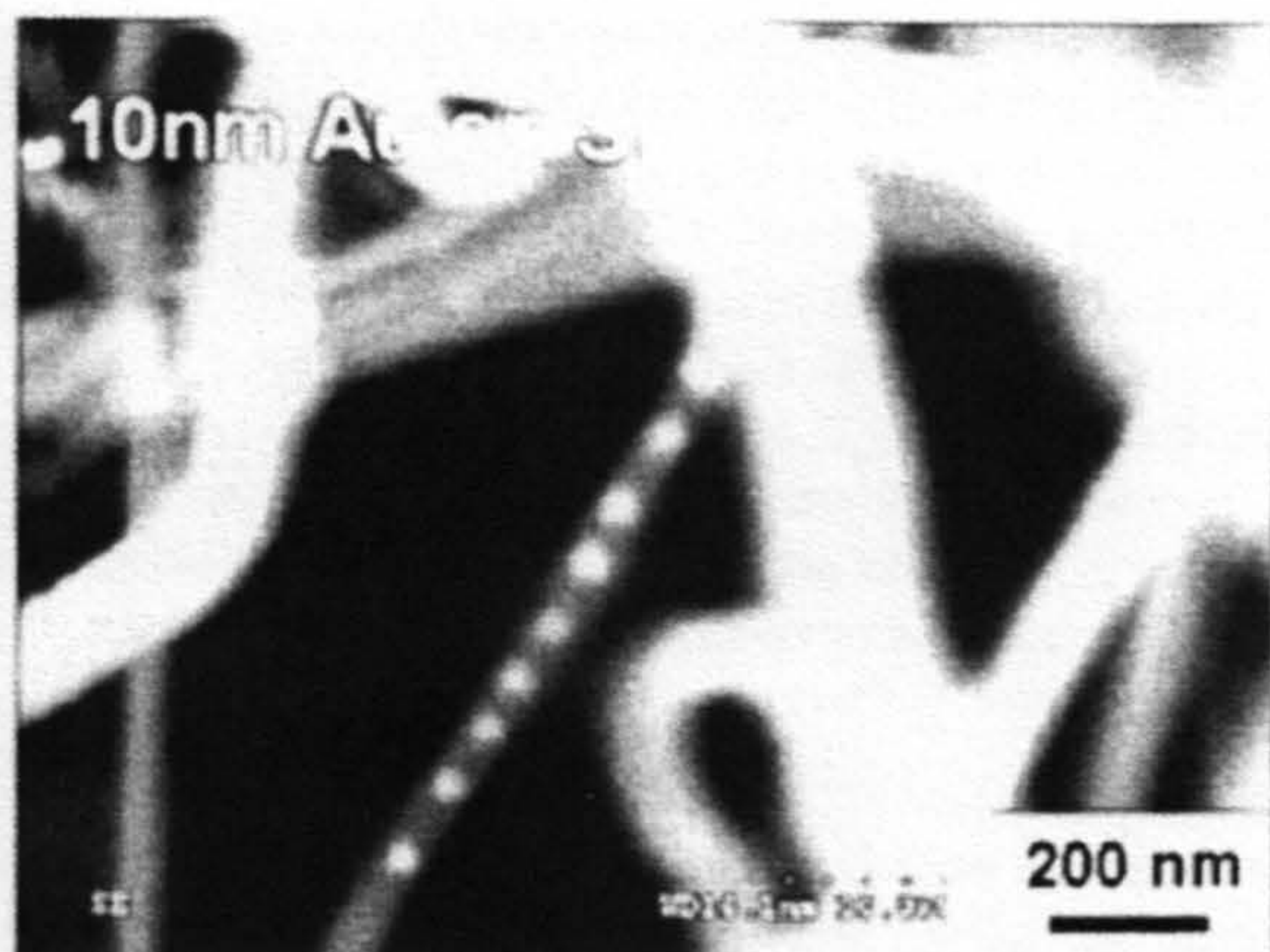


Figure 2. (a) Typical nearly-regular growth of gold bead strings within the silica nanowires; (b) the diffusive pinch-off effect behind the gold drop at the end of the silica wire. The image width in each case is about 2 μm so that the diameter of the main drop is about 300 nm and that of the droplets or beads about 30 to 100 nm.

So there we have the ready-made gold bead-strings for our nano-jewellery. All that remains is to seek publicity (this article!) to advertise it to the bacterial community – except that, being scientists, we would like to understand how the process works. A clue to this may be seen in Figure 2(b), in which the main gold drop seems to be dragging a gold tail behind it in the wire and this tail is pinching off to form a droplet. Indeed this is just what happens in a regular fashion, and the question is “Why?”

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As we saw before, the large gold drop absorbs SiO and oxygen from the surrounding atmosphere and the SiO₂ that is produced diffuses through the drop to deposit at its interface with the growing wire. Because the concentration gradient is larger near the edges of this circular interface than at the centre, the edges grow more rapidly and the interface develops an almost conical depressed shape. After this has reached a moderate depth, its top opening begins to close under the influence of diffusion and ultimately seals off, leaving a small volume of liquid gold within the wire. The enclosed liquid gold volume then gradually becomes a spherical droplet under the influence of its interfacial

free energy. This process then repeats in a regular manner if the gas environment remains stable, giving a chain of gold droplets with a short length of solid silica separating them from each other. These two stages of simple diffusion processes have automatically self-assembled the gold droplet string which later becomes the bead-string of our nano-necklace.

It may be true that we are being unduly hopeful in conjecturing a huge market for the sale of these necklaces to bacteria – perhaps they are much too busy infecting humans and other animals to worry about their appearance. But a regularly spaced string of gold beads may have other applications in the area of nanoelectronics or nanophotonics. We can but hope and meanwhile refine the processes involved.

1. “Gold bead-strings in silica nanowires: a simple diffusion model” N.H. Fletcher, R.G. Elliman and T-H. Kim Nanotechnology 20, 085613 (5pp) (2009)

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Both Neville and Rob have been Presidents of the Australian Institute of Physics.

An extended formulation

The primary aim of this note is to show the simple relation (2) can be extended to apply to crystal-like objects in a space of any number of dimensions. It could well be that this question has already been investigated and resolved by mathematicians, but I have no citations to make. Instead I rely upon the approach of the philosopher Ludwig Wittgenstein, who wrote “I give no sources, because it is indifferent to me whether what I have thought has already been thought before me by others.”

As a first step, equation (2) can be rewritten:

$$N_0 + N_1 = N_2 + N_3 + 1, \quad (3)$$

where N_0 is the number of unconnected spaces contained within the object. For all the cases we have considered so far $N_0 = 1$, but it is easy to construct an example with a higher value of N_0 . Suppose we begin with a simple cube, for which $N_0 = 1$, so that it clearly satisfies (2). Now insert a partition parallel to one of the square surfaces of the cube. Because this partition divides each of the edges and faces that it intersects into two parts, this increases N_0 by 4, N_1 by 5 and N_2 by 8, and, because the interior volume is now divided into two sections, increases N_3 by 1. The relation (2) is still satisfied, and further divisions of the interior volume have similar results, provided they do not result in any torus-like structures.

If we examine the dimensionality of the objects referred to by terms in equation (3), we see that those on the left-hand side have dimension 0 and 1 respectively, while those on the right-hand side have dimensionality 1 and 3, omitting consideration of the final numerical term. This observation leads us to propose a generalization of (3) of the form

then three remains a conjecture, but a steady progression through dimensionality exists. To convert from an object of dimensionality zero to a dimensionality of one in a space of dimensionality one or higher we must add another point not lying in its zero-dimensional space and join them with an object of dimensionality one (a line). To convert from an object of dimensionality one (a line) to a minimal object of dimensionality two (a triangle), we must connect its vertices to a point not lying within its one-dimensional space. To convert from a triangle to a minimal object of dimensionality three, we must connect its vertices to an additional point not lying in its plane, thus making a tetrahedron. This leads us to surmise that, in order to create a minimal object of dimensionality four we must take a tetrahedron and connect its vertices to an extra point not lying in the three-dimensional space that it occupies. Unfortunately it is nearly impossible for us to visualize such an object! Once again, following the discussion of three-dimensional objects, the applicability of the result must be restricted to objects with compact topology, eliminating those with the analog of toroidal structure.

Conclusion

This short note takes a well-known theorem relating to the geometry of polyhedral crystalline forms in three dimensions, expresses it in a notation that is applicable in any number of dimensions, and conjectures that this extended version, which is demonstrably correct for objects in spaces of dimensionality three or less, can also be applied to similar objects of higher dimensionality embedded in spaces of higher dimension. With theoretical physics expanding into spaces with dimensions higher than twelve, this conjecture is perhaps worthy of further attention and could even prove useful. (Perhaps string theorists already know all about it)