palaeogeographical reconstructions describing changes in shorelines, large-scale topography and the position of the landmasses over the past 540 million years, as well as by climatic simulations showing the concomitant changes in the water cycle. The model simulates elevation on land at high resolution (5 kilometres) using a source-to-sink approach, which means that sediments eroded on land are tracked while they travel in river networks until they reach the ocean. By doing so, the model also represents the location and magnitude of deposition of sediments on the continents.

The model was calibrated and validated in the present day before being used to analyse the deep geological past. This approach forms part of current efforts to build a virtual planet, in which a variety of processes are integrated to generate a digital twin of Earth, permitting researchers to gain mechanistic understanding of the coupling between Earth's surface and its interior.

The simulations demonstrate a striking, positive correlation between marine biodiversity and the flux of sediments delivered to the ocean (Fig. 1a). Nutrients constitute the fundamental building blocks required by organisms to generate their tissues. In the ocean, nutrients come mainly from the river-provided input of dissolved chemical species generated by the alteration of rocks on land. Postulating that the quantity of nutrients delivered to the ocean scales with the sedimentary flux, the authors interpret the correlation between the simulated sedimentary flux and marine biodiversity as reflecting the nutrient-driven variation in the carrying capacity of the oceans.

For land, the authors designed an index representing the landscape's capacity to host diverse species. This index combines the extent of sediment cover on land and the landscape variations (heterogeneity). The former represents the area available for land plants to develop their rooting networks, whereas the latter is a way to represent the number of distinct ecological niches, and thus the potential number of species. The biodiversity of land plants strongly correlates over time with this index, suggesting that landscape dynamics have also set the agenda for the evolution of land plants during the past 540 million years (Fig. 1b).

These results are innovative in many ways. They explain the evolution of terrestrial and marine biodiversity and notably suggest that limited sediment cover and low landscape heterogeneity delayed the development of land plants before the Devonian period — which would explain the previously mysterious temporal lag of more than 100 million years between the increase in marine biodiversity and the subsequent increase in terrestrial biodiversity. This study offers a fresh reading of biodiversity on geological time scales — one that considers a carrying capacity of the environment, but does not need to account explicitly for ecological innovations and evolution. It thereby raises questions about existing models that do account for such factors[3,4].

In the authors' framework, several of the largest mass extinctions followed large drops in the sediment flux to the ocean (Fig. 1a). This is notably the case for the largest such mass extinction, at the Permian–Triassic boundary, which post-dates the largest decrease in sediment flux simulated over the past 540 million years. The possibility that nutrient shortage could constitute an important precondition for extinctions contrasts with the widely held idea that nutrient increase would drive these extinctions[5]. In this view, a consequence of nutrient increase is that photosynthetic algae in the shallow ocean would produce extra organic matter, which would then be degraded by bacteria in deeper water consuming dissolved oxygen, ultimately leading to ocean deoxygenation.

Simulations such as this work by Salles and colleagues could be refined by including information on the types of rock eroded on land and refining details concerning the location and elevation of ancient mountains. Moreover, the conclusions are based on temporal correlations, and alternative interpretations are possible. The correlation between marine biodiversity and the simulated sediment flux might imply that biodiversity curves mostly reflect preservation biases — with strong fossil records, and thus high levels of documented biodiversity, corresponding to periods when marine sedimentation rates are high.

To go beyond temporal correlations and to assess causality, it would now be beneficial to quantify the effect of landscape dynamics on biodiversity using macroecological models[6] based on the high-resolution, open-access layers of environmental data produced in this study (see go.nature.com/41pqrz8). This would help to confirm or revise the interpretations. It might also assist in explaining some model–data mismatches, such as a lack of pointers to the Great Ordovician Biodiversification Event[7] in the simulations.

Alexandre Pohl is in Biogéosciences, UMR 6282 CNRS, Université de Bourgogne, 21000 Dijon, France.
e-mail: alexandre.pohl@u-bourgogne.fr

1. Salles, T., Husson, L., Lorcery, M. & Boggiani, B. H. *Nature* **624**, 115–121 (2023).
2. Sepkoski, J. J., Bambach, R. K., Raup, D. M. & Valentine, J. W. *Nature* **293**, 435–437 (1981).
3. Vermeij, G. J. *Paleobiology* **3**, 245–258 (1977).
4. Cermeño, P. *et al. Nature* **607**, 507–511 (2022).
5. Hülse, D. *et al. Nature Geosci.* **14**, 862–867 (2021).
6. Hagen, O. *et al. PLoS Biol.* **19**, e3001340 (2021).
7. Ontiveros, D. E. *et al. Nature Commun.* **14**, 6098 (2023).
8. Sepkoski, J. J., Jablonski, D. & Foote, M. J. *A Compendium of Fossil Marine Animal Genera* (Paleontological Research Institution, 2002).
9. Nildas, K. J., Tiffney, B. H. & Knoll, A. H. *Nature* **303**, 614–616 (1983).

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Nanotechnology

Self-assembling structures close the gap to trap light

Takashi Asano

An innovative method uses the intrinsic attractive force between silicon surfaces that are separated by a tiny gap to engineer structures that can confine light — offering an ideal set-up for manipulating single photons. **See p.57**

Light is generally thought of as an electromagnetic wave that propagates through space, but it is actually possible to trap it in a tiny region for a short time[1–5]. Confining light increases its energy density, and thus strengthens the intensity of its electric field. This enhances the interaction between light and matter — an effect that can be used to generate single photons on demand[6], enabling the processing of quantum information[7–9]. One of the most promising light-confinement techniques uses silicon, and can therefore benefit from the advanced silicon-processing technologies of the electronic-circuit industry. But this method requires the silicon to be fabricated with nanoscale features that are difficult to engineer. On page 57, Babar *et al.*[10] report a clever approach that uses attractive interactions to create gaps that solve the problem.

Two main techniques are used to confine light: plasmonics[11,12], which involves metallic nanostructures; and photonics[1–4], which uses materials, known as dielectrics, that are transparent to light and have a high refractive index. Plasmonics works on the principle that the wavelength of light becomes shorter

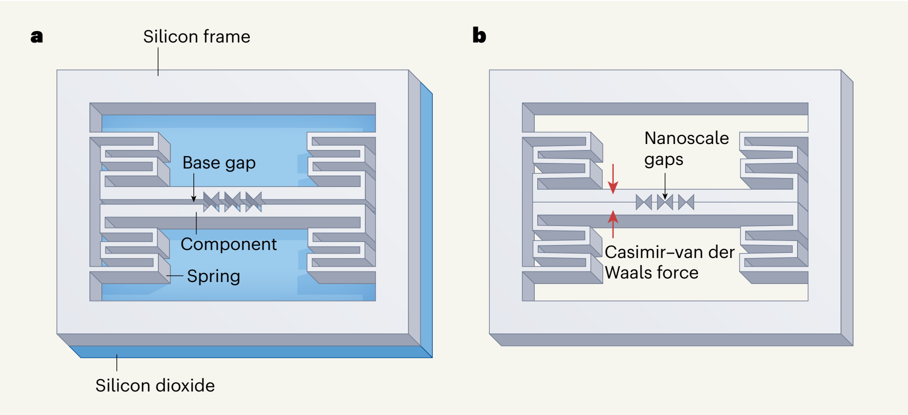

Figure 1 | A method for creating nanoscale features in a silicon structure. Babar *et al.*[10] made a silicon structure with nanoscale gaps that can be used to confine and manipulate light. **a**, The authors first prepared a silicon layer attached to a layer of silicon dioxide, and fabricated two components (supported by a silicon frame and springs) from the silicon layer. The components were separated by a 'base gap' that was engineered to be wider at certain points. **b**, Babar *et al.* then removed the silicon dioxide layer, leaving the silicon components supported only by the springs. Thus exposed, the components were subject to an attraction known as the Casimir–van der Waals force. This force brought the components together, closing the base gap and creating nanoscale gaps that could trap light.

when it propagates along a metal surface. This makes it possible to confine light to a small region that has roughly one-thousandth of the volume of a cube whose sides are equal to the wavelength of light in a vacuum[11]. However, the light also loses energy quickly because some of it gets absorbed by the metal. The strength of the light–matter interaction depends on both the strength of the electric field and the interaction time, so the short timescale on which this loss of energy occurs can be problematic.

By contrast, a dielectric material can be used to confine light for a long time (up to one million times longer than can be achieved with plasmonic devices) in a region with a volume that is roughly light's wavelength cubed, and this enhances the light–matter interaction[5]. The interaction can be further boosted by engineering confinement structures with bow-tie shapes or narrow gaps that locally increase the strength of the electric field at the neck of the bow tie or in the gap[13]. This enhancement can, in effect, reduce the volume of the region in which light is confined. However, making such structures is difficult because the width of the gap or the bow-tie neck must be very small — around 10 nanometres at most — to achieve the level of spatial confinement that is realized in plasmonic cavities[14].

Silicon is widely used as a dielectric material for confining light. But, although technologies for processing the element are now very advanced, it is challenging to produce features at a scale of less than 10 nm on a silicon plate that is around 200 nm thick (the requisite thickness for confinement). This is because such features are typically formed by preparing a kind of stencil that sits on top of the silicon, and then removing the areas outside the stencil by applying ionized gas. Perfectly vertical edges are therefore difficult to fabricate in such a thick layer, and tiny gaps are especially challenging because their narrowness prevents the flow of gas.

In 2018, researchers made a bow-tie structure with a neck width of 12 nm, and created a gap-like effect by modifying the top of the structure to form a vertical 'v' shape at the neck of the bow tie[15]. Then, last year, members of the same research group as Babar *et al.* produced a bow-tie structure with a neck width of 8 nm (ref. 14). This structure can theoretically have a light-confinement volume that is less than one-thousandth of light's wavelength cubed. However, miniaturizing the structure further was thought to be a tough proposition.

Now, Babar *et al.* have succeeded in creating a structure with a gap that is 2 nm wide and 220 nm thick. They did so by first creating two silicon components separated by a wide gap, and then narrowing the gap through a process of self-assembly (Fig. 1). The components were fabricated from a 220-nm-thick layer of silicon, attached to a layer of silicon dioxide, using the standard technique involving a stencil and ionized gas. The authors separated the components by a 'base gap', but engineered this gap to vary in width at certain points. The whole silicon structure was attached to a frame by thin silicon springs.

The authors removed the oxide layer using hydrogen fluoride gas, leaving the silicon components supported only by the springs. When silicon surfaces are separated by a nanoscale gap, they are subject to an attraction known as the Casimir–van der Waals force, and this effect brought the components together. The base gap closed completely, but in the areas in which the gap width was different, small gaps formed that could be used to confine light.

The individual techniques that Babar and colleagues have built on are all well known in the field of micro-electromechanical systems. For example, the self-assembly of a structure by releasing components from a 'sacrificial' layer is an established method[16], but the scale on which the authors use it differs from that in previous applications, as do the driving forces involved.

The attraction caused by the Casimir–van der Waals force is also well known, but is usually considered to be a negative effect, because it can make movable parts immobile, for example[17]. The authors have instead taken advantage of this force to create a 2-nm gap using ordinary semiconductor processes. And because the gap is wide (approximately 50 nm) before the Casimir–van der Waals force closes it, luminescent materials can be deposited on its surface to create a single-photon source before the silicon dioxide is removed.

Babar and colleagues' technique could be applied to other technologies in which nanoscale gaps are useful, such as DNA sequencers. Before these applications are realized, however, further work will be needed to ensure that the size and shape of the gap can be reliably reproduced, as well as the surface smoothness and verticality that are required to obtain very narrow gaps. Once these issues are resolved and the method becomes widely available, it will be exciting to see how this ingenious approach can be applied to build nanoscale structures that have not so far been feasible to produce.

Takashi Asano is in the Quantum Optoelectronics Laboratory, Kyoto University, Kyoto 615-8510, Japan.
e-mail: tasano@qoe.kuee.kyoto-u.ac.jp

1. Noda, S., Chutinan, A. & Imada, M. *Nature* **407**, 608–610 (2000).
2. Painter, O. *et al. Science* **284**, 1819–1821 (1999).
3. Akahane, Y., Asano, T., Song, B.-S. & Noda, S. *Nature* **425**, 944–947 (2003).
4. Han, Z. *et al. Opt. Commun.* **283**, 4387–4391 (2010).
5. Asano, T., Ochi, Y., Takahashi, Y., Kishimoto, K. & Noda, S. *Opt. Express* **25**, 1769–1777 (2017).
6. Strauf, S. *et al. Nature Photonics* **1**, 704–708 (2007).
7. Kimble, H. J. *Nature* **453**, 1023–1030 (2008).
8. Reiserer, A. & Rempe, G. *Rev. Mod. Phys.* **87**, 1379–1418, (2015).
9. Volz, T. *et al. Nature Photonics* **6**, 605–609 (2012).
10. Babar, A. N. *et al. Nature* **624**, 57–63 (2023).
11. Miyazaki, H. T. & Kurokawa, Y. *Phys. Rev. Lett.* **96**, 097401 (2006).
12. Santhosh, K., Bitton, O., Chuntonov, L. & Haran, G. *Nature Commun.* **7**, 11823 (2016).
13. Hu, S. & Weiss, S. M. *ACS Photonics* **3**, 1647–1653 (2016).
14. Albrechtsen, M. *et al. Nature Commun.* **13**, 6281 (2022).
15. Hu, S. *et al. Sci. Adv.* **4**, eaat2355 (2018).
16. Rogers, J., Huang, Y., Schmidt, O. G. & Gracias, D. H. *MRS Bull.* **41**, 123–129 (2016).
17. Buks, E. & Roukes, M. L. *Phys. Rev. B* **63**, 033402 (2001).

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