

So, even if this phase-change material shows Anderson localization, can electron correlations still play a role? Not particularly, as in GeSb_2Te_4 these correlations are small and do rule out a Mott transition¹. In the Mott picture, crystalline GeSb_2Te_4 should always be metallic. Yet it is not. Rather, Siegrist and colleagues derive a minimum metallic conductivity whose value agrees well with Mott's prediction. Its occurrence is not that unusual and has been found previously in doped and amorphous semiconductors^{4–6,9}. But it is not obvious⁴ how the minimum conductivity can be reconciled with the critical exponents for the Anderson model. And it is surprising that this minimum metallic conductivity is observable at room temperature in bulk samples.

Does this mean that the Anderson picture is not valid? It certainly means that further investigations are needed for a better understanding and that phase-change materials might become a new toy class for localization studies, with the MIT driven by changing not the density but the mobility of the charge carriers.

For application purposes, it is noteworthy that this mobility change can be tuned by annealing to achieve different resistance values in the same sample (see Fig. 2). This would be important for applications in non-volatile-memory devices. Tuning the resistance by annealing is an old technique¹⁰ and is applied in the electronic industry¹¹. But in phase-change materials the resistance can be

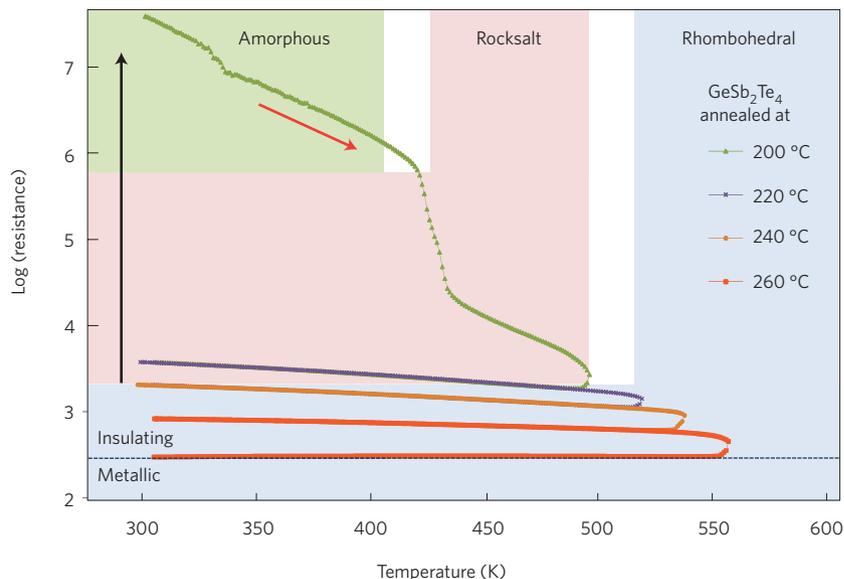


Figure 2 | Dependence of the resistance of a single sample on annealing in several temperature cycles. The constant resistance after annealing at 260 °C indicates the MIT.

switched on a nanosecond timescale. This is promising for the application in multilevel memory storage. Understanding why and how the electrons are localized, or not, might shift the border between good and bad memory. □

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COLLOIDAL SELF-ASSEMBLY

Patchy from the bottom up

The realization of a self-assembled kagome lattice from colloids with attractive hydrophobic patches offers a simple but powerful example of the bottom-up design strategy.

Flavio Romano and Francesco Sciortino

Writing in *Nature*, Steve Granick and co-workers report an exciting experimental example of a bottom-up design, in which patchy colloids — colloidal particles with attractive spots on their surface — were created *ad hoc* to self-assemble into a two-dimensional kagome lattice¹ (an arrangement of intertwined triangles, as shown by the dashed lines in Fig. 1). Such a complete bottom-up process — from the design of the patchy particles to the experimental detection of the desired target structure,

including the colloids' synthesis — has rarely been reported. Indeed, despite recent emphasis on the relevance of the bottom-up approach for the production of new colloidal materials, research in the field has mostly focused on the synthesis and characterization of patchy colloids whereas less effort has been devoted to the study of the emerging structures arising from the particles' spontaneous assembly — such as wires, sheets, micelles or three-dimensional crystals. As patchy colloids^{2–4} promise to become the elementary bricks of tomorrow's

self-assembled materials, there is much expectation in the outcome of recent efforts towards the creation of particles that interact through non-spherical, patchy potentials. The challenge is to achieve targeted ordered or disordered self-assembled structures through the rational design of patchy particles, be it controlling particle shape and/or particle patterning. In this regard, the work by Granick and collaborators is a beautiful and simple illustration of what is now possible with this strategy.

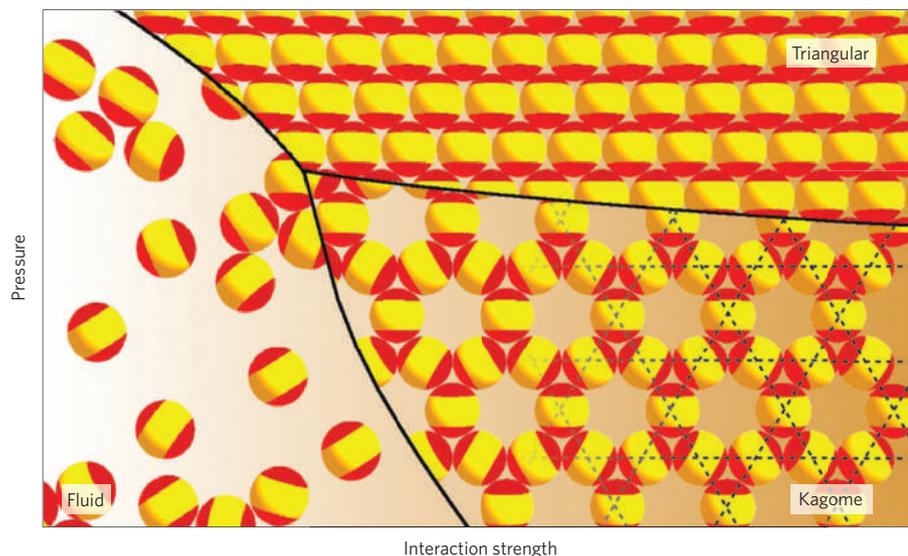


Figure 1 | Sketch of the phase diagram of triblock Janus particles⁶. Self-assembly occurs when the strength of the interaction between patches (depicted in red) is large enough to overcome the random forces arising from the thermal jiggling of the particles. In this case they crystallize into a kagome lattice, or a closed-packed triangular lattice at higher density.

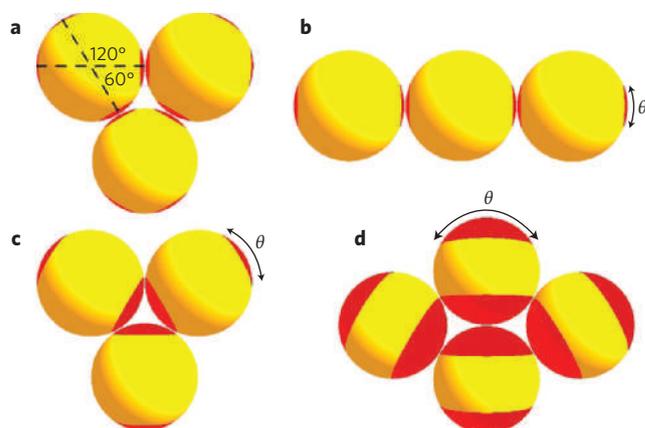


Figure 2 | Cartoons of patchy colloids with (red) patches centred along the particles' equator. **a**, A colloidal kagome lattice could, in principle, self-assemble from colloids with four small patches centred at the specific particle–particle contacts of the lattice. **b–d**, Role of the angular width of the patch, θ , in the possible number of hydrophobic contacts per patch for triblock Janus colloids. **b**, At small θ values, particles can form only one contact per patch, and only chains of particles are possible. **c**, At intermediate θ , each patch is sufficiently wide to make two contacts (but not three). This is the case of the colloids synthesized by Granick and co-authors¹, which self-assemble into the structures described in Fig. 1. **d**, For large θ , a big patch can make more than two contacts, which may result in structures other than the kagome lattice.

The naive design of patchy particles that self-assemble into a kagome lattice would consist of spheres whose surfaces are each decorated with four small patches, symmetrically located along the equator at alternating intervals of 60° and 120° so that they match the distribution of the four contacts per particle observed in the target lattice (Fig. 2a). However, patterning a particle's surface with patches in such

a sophisticated geometry would require a very careful and controlled synthesis process that is beyond today's experimental reach. Granick and colleagues, though, came up with a simpler solution. They synthesized hydrophilic micrometric latex spheres with two opposite polar caps¹, which were made hydrophobic through the deposition of self-assembled monolayers of hydrophobic chains, preceded by glancing

angle deposition⁵ of titanium and gold. The particles thus have an electrically charged band in-between the hydrophobic caps (Fig. 2c), and because of this geometry they were named 'triblock Janus' colloids. Adding salt to the solvent effectively screens the repulsion of the middle bands and enhances the hydrophobic attraction between the polar patches. Granick and co-authors proved that the kagome lattice can be realized using triblock Janus colloids if one makes an accurate choice of the patch angular width, θ . The key point here is that the θ chosen must be sufficiently large to allow for more than one contact per patch but sufficiently small to avoid patches forming more than two contacts (Fig. 2b–d).

Why are just two simple patches so effective for the self-assembly of the kagome lattice? In our opinion, two important elements lie behind the winning intuition of Granick and colleagues. First, the higher symmetry of the triblock Janus colloids facilitates their production process, well within today's experimental means⁵. And second, the larger and circular geometry of the patches makes the bonding volume — the number of possible orientations of two patchy particles compatible with the formation of hydrophobic contacts — significantly larger than that in the four-patch case. Such increase in bonding (orientational) entropy has a double effect: it decreases the strength of the attraction at which bonding takes place, making it easier for the thermal energy to anneal the defects of the target crystal structure, and it reduces both the kinetic bottlenecks along the crystallization path and the appearance of disordered traps associated with glass/gel formation. The very detailed information on the crystallization process supports this view (see supplementary movies of ref. 1). Indeed, the self-assembly of the kagome lattice smoothly processes through a sequence of steps by which the number of isolated particles decreases in favour of the formation of chains of oppositely bonded particles, which then slowly rearrange themselves to form the triangular elements of the structure. The dynamics of the crystallization pathways, accurately reproduced for triblock Janus colloids in our recent numerical simulations⁶, can also provide a stringent test of current nucleation theories in two dimensions.

Notably, the work of Granick and co-workers raises several stimulating questions. First, is the rational design developed for the self-assembly of the kagome lattice directly transferable to other crystal structures, in particular in three dimensions? This is relevant to the design

and assembly of photonic materials⁷, which would greatly benefit from a reliable method of crafting colloidal crystals. Second, how can one incorporate to the rational design strategy the selection of the target crystal when various competing structures are possible? In fact, owing to the short-ranged nature of the attractive patch–patch interaction, the free energy of crystal structures with similar local environments but different symmetries (for example, cubic and hexagonal close packed, or cubic and hexagonal diamond) can be very close. We believe that theoretical calculations that evaluate the stability region of the different structures in the phase diagram and suggest the best choice of the external conditions will greatly help in this regard. Indeed, our recent numerical simulations⁶ of the

two-patch Kern–Frenkel model^{8,9} — a simple model of the triblock Janus particles that is able to accurately reproduce the self-assembly and crystallization kinetics of the kagome lattice — suggests that the closed-packed triangular lattice becomes the preferred structure at large densities² (Fig. 1). Moreover, it is expected that the design of the shape of the patches and of the particles' symmetry makes the control of the target-structure symmetry possible. Interestingly, the glancing angle deposition technique for particle patterning⁵ can be used to encode patches with non-identical shapes and orientations, thus providing high versatility to the synthesis of Janus colloids. Surely, both the design and realization of new patchy particles will soon bring more exciting news. □

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ARTIFICIAL ATOMS

Shape the wave

Tunnelling and capacitance spectroscopies are able to image the wavefunctions of electrons in atom-like solid-state systems as they are shaped by an external magnetic field.

Massimo Rontani

A critical requirement of quantum information technology is the fine tuning of quantum states. For example, in solid-state proposals where electron spins encode information, logic operations rely on the control of exchange interactions between electrons¹. These interactions depend on the overlap between electron wavefunctions, hence, they are extremely sensitive to the spatial extent of quantum states, which in turn may be modified by external forces. A most useful task for this kind of proposal — as well as for other applications — is to study how external perturbations modify the shape of the wavefunctions, through proper mapping tools. Being able to do this is also of fundamental interest, because of the current limitations in imaging and manipulating single quantum states through techniques such as scanning tunnelling spectroscopy. Writing in *Physical Review Letters*, Amalia Patané² and Wen Lei³, together with their colleagues, have independently presented images of atom-like wavefunctions as they were spatially compressed by the magnetic field.

Whereas many experiments measure energies and intensities of transitions between different quantum states, the

tunnelling and capacitance spectroscopies used, respectively, by Patané and Lei probe the electron probability density with energy and space selectivity. As the density embodies the contributions of

those orbital states that have like energies, in general there is no one-to-one relation between measured signal and wavefunction modulus. This lucky connection is warranted only if the energy levels are

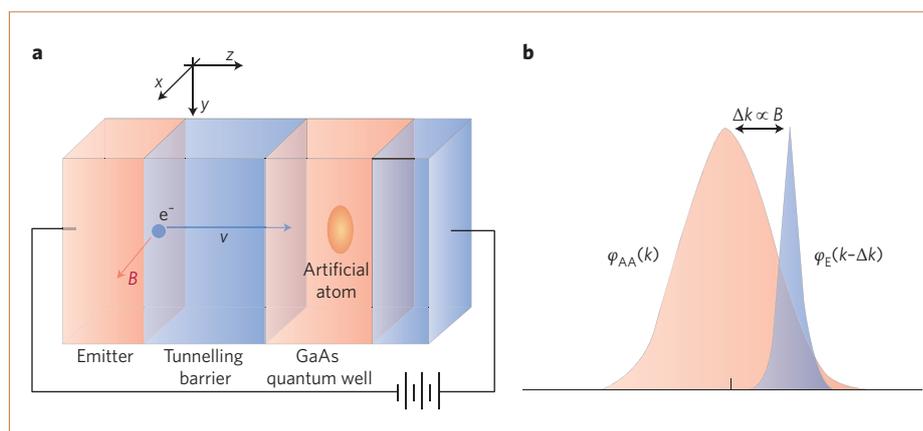


Figure 1 | The wavefunction imaging technique. **a**, Experimental set-up in a nutshell. Electrons tunnelling from the emitter into the artificial atom gain momentum Δk along the y axis if the magnetic field with magnitude B is applied along x , as a consequence of the Lorentz force (v is the electron velocity parallel to the z axis). The tunnelling transition amplitude is proportional to the Fourier transform of the artificial-atom wavefunction in the in-plane momentum space, resolved at the value of the momentum gain Δk . The tunnelling rate is measured in both tunnelling- and capacitance-spectroscopy set-ups. **b**, Overlap between typical emitter and artificial-atom wavefunctions. $\varphi_{AA}(k)$ and $\varphi_E(k-\Delta k)$, wavefunctions of artificial atom and emitter, respectively; k , momentum; Δk , change in momentum proportional to field B . Adapted from ref. 11, © 2002 APS.