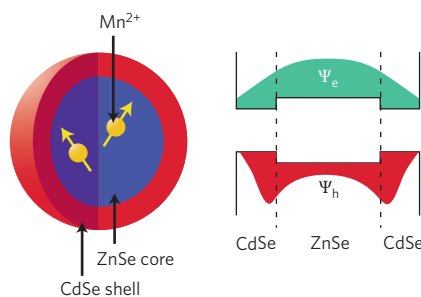


means that they interact more weakly<sup>6</sup> with Mn through the exchange interaction than they would had the overlap of their wave function been greater (for example, such as in bulk DMS). Incidentally, the weaker confinement also pushes the quantum dot photoluminescence below that ascribed to internal Mn optical transitions, which avoids part of the electron–hole pairs recombining through the states around the dopants — an approach also used in self-assembled quantum dots of CdMnTe (ref. 7).

Modifying the overlap between wavefunction and magnetic atoms can have greater effects than simply altering the strength of the exchange interaction, as shown by Merkulov and colleagues with quantum wells<sup>8</sup>. The reduced symmetry can activate the so-called ‘kinetic component’ of the exchange interaction, which in turn can lead to the sign of the spin splitting being reversed. This sign is closely linked to the polarization properties of the light emitted by the quantum dots. In other words, we could say that by simply controlling the thickness of the outer layer, Bussian *et al.* are able to control the strength, and even the sign, of the exchange interaction that is at the heart of spintronics.

Although this study has been performed on an ensemble of nanocrystals, the experiments are likely to be repeated soon on single nanocrystals, providing even



**Figure 1** | Core/Shell Mn:ZnSe/CdSe quantum dots. The graphs on the right show that although the conduction electron wavefunction ( $\psi_e$ ) has its maximum in the centre of the core, that of the holes ( $\psi_h$ ) has peaks in the CdSe shell.

more convincing evidence of the observed tunable exchange interaction. Another approach may be to further dilute the content of Mn in nanocrystal cores and obtain a single dopant atom. Two magnetic ions in a nanocrystal is probably the least favourable situation from the perspective of giant spin-splitting: the interaction of the localized Mn spins in ZnSe happens to be antiferromagnetic, and so the total magnetic moment of the pair vanishes. Dealing with a single magnetic ion per nanocrystal would be much more desirable from that perspective and should be feasible, as suggested by studies of epitaxial, self-assembled quantum dots<sup>9,10</sup>.

A final consideration is that decreasing the overlap between electrons and holes also reduces the probability of radiative recombination. On the downside, this makes the nanocrystals a less efficient light source. However, they are more useful for logic and memory applications.

The importance of the study by Bussian *et al.* is it demonstrates that intrinsic quantum properties of DMS nanocrystals can be controlled by as simple a parameter as overlayer thickness. This is comparable to the bandgap engineering revolution made possible by adjusting the width of the quantum wells in optoelectronic devices. Before realistic applications can be considered, there are several obvious issues that need to be solved — for example, the fact that the operation of such systems only occurs at low temperature. □

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## FERROELECTRICS

# Start the presses

A simple nanoimprinting method creates arrays of ferroelectric polymer structures suitable for low-cost, non-volatile memories.

Stephen Ducharme and Alexei Gruverman

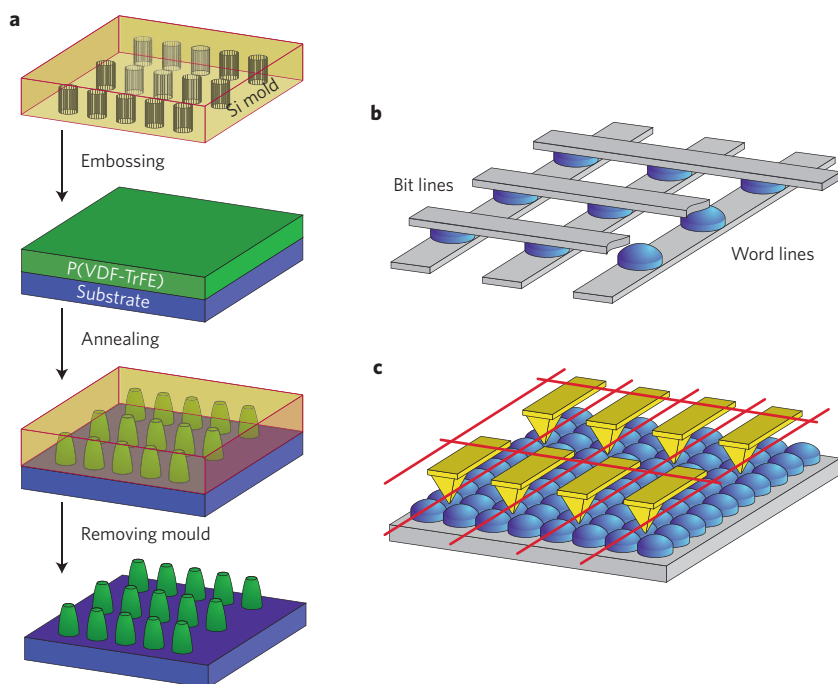
Almost since the dawn of computing, digital information has been stored predominately in two kinds of structure: silicon transistor arrays (for fast, volatile random-access memories) and magnetic media (for low-cost, non-volatile mass data storage). A relative newcomer is the flash drive, a form of semiconductor memory that provides both random-access and non-volatile storage, but at higher cost, with inferior speed and compromised operating lifetime. As with earlier technologies, flash advances are steadily following Moore’s law, making it difficult for fundamentally new technologies to get a foothold in the market. Ferroelectric memories, which store data in a bistable

electrical polarization state that can be switched by a short voltage pulse, are, like flash, non-volatile and provide random-access, yet are inherently faster and have greater operating lifetimes. In spite of their relatively high costs, ferroelectric memories have already found applications in consumer electronic devices, including smart debit cards and the Sony Playstation 2. On page 62 of this issue, Zhijun Hu and co-workers report a simple but effective method of fabricating ferroelectric bit arrays that could be used as low-cost, non-volatile random-access memories for emerging organic electronics technologies<sup>1</sup>.

The nanoimprinting method for fabricating ferroelectric bit arrays is

conceptually simple and remarkably effective (Fig. 1). A continuous polymer film approximately 50-nm-thick is formed across the substrate by solvent spin-coating, in the same fashion as photoresist is applied onto semiconductor wafers in integrated circuit fabrication. The film is then heated into a non-ferroelectric liquid-crystalline state and a mould consisting of a regular nanocavity array is pressed into the film. As the film cools back into the ferroelectric crystalline state, the mould is removed. The resulting regular array of nanostructures, which we will call ‘nanomesas’, is highly uniform in size and shape.

Ferroelectric bit arrays have long been considered promising candidates



**Figure 1** | The nanoimprinting method and the two ways it can be used in non-volatile random-access memory and data-storage devices. **a**, A nanoimprinting mould embosses the polymer by hot pressing, leaving a well-ordered array of ferroelectric nanomesas. **b**, A cross-point memory, which is addressed by 'word line' contacts on the bottom and 'bit line' contacts on top. **c**, A multiprobe array.

for high-capacity ferroelectric memories and data storage<sup>2</sup>. So far, the two main approaches for producing regular arrays of high-quality isolated ferroelectric bits have encountered difficulties. One approach is to use conventional photolithography to etch the desired pattern into the thin film. However, the problem with ferroelectric polymers is that the films start out as a highly inhomogeneous structure, with nanoscale crystals of varied size, shape and crystallographic orientation. Lithographic patterning only removes some of the film, leaving bits with lots of defects and imperfections and highly variable properties — both undesirable traits for memory technology. The second approach is to exploit short-range interactions to spontaneously form ferroelectric nanomesas. This self-assembly method can produce ferroelectric polymer nanomesas of outstanding crystallinity and uniformity. The arrays are poorly ordered, however, because the growth of individual nanomesas is not spatially controlled, and they don't necessarily align neatly with their neighbours.

Nanoimprinting is indeed a conceptually simple way to make ordered arrays of nanostructures, as demonstrated previously for ferroelectric lead zirconate–titanate printed from a sol–gel precursor<sup>3</sup>. What makes the achievement of Hu *et al.*

remarkable is the uniformity and quality of the nanomesas made from ferroelectric polymers, which they achieve through careful control of imprinting and annealing conditions. The arrays are well-ordered and uniform in both morphology and ferroelectric properties. Of critical importance is the hot moulding that

**We now have all the  
necessary ingredients to  
print inexpensive, disposable  
organic memory chips.**

occurs in the non-ferroelectric liquid-crystalline phase, allowing the nanomesa to optimize their crystal structure before cooling into the rigid ferroelectric phase. This is evident from electron diffraction results, which show that the nanomesas are uniformly crystalline with the electric polarization axis optimally oriented normal to the top surface. Hu and colleagues even demonstrate the selective switching of the electric polarization of individual nanomesa bits between their on and off states. Hysteresis loops of individual nanomesas reveal that the switching is well-controlled and highly reproducible from bit to bit. These features are essential for a binary memory array.

The work of Hu *et al.* shows that the nanomesa arrays are ready to be integrated into non-volatile random-access memory and probe-based data-storage devices. Actual random-access memory devices will probably be more complicated than the simple crossed electrode pattern shown in Fig. 1b. A more likely scheme would integrate each ferroelectric nanomesa with a transistor, where the ferroelectric directly provides the charge signal (as found in currently available ferroelectric memories)<sup>2</sup>. Alternatively, the ferroelectric nanomesas can be placed on top of a field-effect transistor to directly control the transistor action and to make a non-volatile form of the ubiquitous memory cell used in nearly all memory chips.

On the other hand, the ferroelectric nanomesa arrays can be an ideal recording media in probe-based storage devices. In this approach, similar to the IBM millipede concept used to burn nanoscopic pits into a polymer layer<sup>4</sup>, a multi-probe array is used for massive parallel writing and read-out of individual bit states (Fig. 1c). Physical separation of the nanomesas eliminates the problem of cross-talk between the bits and potentially allows Tb inch<sup>-2</sup> storage density, making cheap and durable bit arrays fabricated by nanoimprinting a valuable alternative to inorganic ferroelectrics and polymer thermoplasts in high-density storage devices.

The next logical step is to integrate these memory elements into electronic circuits, and there are already several promising methods for fabricating integrated electronics entirely from organic materials, also using nanoimprinting and nanoimprinting methods<sup>5</sup>. With the development of nanoimprinted high-quality ferroelectric nanomesa arrays, it seems that we now have all the necessary ingredients to print inexpensive, even disposable, memory chips for ubiquitous computing. Start the presses! □

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