Atoms join in the race for lithography in the next century

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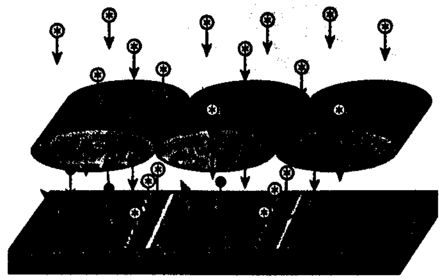
An impressive technology has been developing since the 1960s to make the tiny electronic devices that form the basic circuits in today's computer chips. Huge ultraclean buildings filled with lithography machines costing $2–4 million each churn out 20 000 silicon wafers every month, producing more transistors per square millimetre for less money than ever before. But many experts say that the steady increases in circuit density will come to an abrupt halt if we do not come up with some radical new ideas.

The problem is that the features made by conventional optical lithography cannot be shrunk indefinitely. The laws of diffraction dictate that the only way to make feature sizes smaller is to shorten the wavelength of the light. Yet the materials needed for lenses and other optical components are not effective at shorter wavelengths, and so optical lithography cannot pattern feature sizes less than about 100 nm.

Now, Mara Prentiss and colleagues at Harvard University in the US have demonstrated an intriguing new type of lithography that could be used for patterning devices below the 100 nm barrier (*Science* 1998 **280** 1583). This approach uses a beam of metastable rare-gas atoms, each one carrying a tiny payload of energy, which are guided onto a surface by laser light. The researchers have used the technique to pattern a silicon wafer with an array of lines 65 nm wide and separated by 401 nm.

Lithography in any form is the art of transferring a pattern onto a substrate. Optical lithography uses special lenses to project the reduced image of a mask onto a wafer covered with a photosensitive resist. Photons striking the resist alter it chemically, making it harder or softer (depending on the type of resist). Resist in the softer regions is removed with chemicals and an etching step transfers the pattern to the silicon wafer.

But the use of lithography to produce feature sizes smaller than 100 nm is a critical problem for the semiconductor industry. Research teams around the world are now investigating several alternative techniques for achieving the required resolution in a cost-effective way, including electron-beam, ion-beam and x-ray lithographies. Each technique has its advantages and disadvantages, and no-one yet knows which will be the method of choice in the semiconductor factories of the 21st century.



A standing wave of laser light can pattern a beam of metastable atoms (green). Away from the regions close to the zero intensity, the light excites the atoms to a highly energetic level from which they rapidly decay into the ground state. The ground-state atoms (red) are simply reflected from the surface. The metastable atoms that reach the surface deposit their energy in the resist and cause residual hydrocarbons to adhere permanently to the substrate.

The new process, often dubbed "atom lithography", reverses the conventional roles played by light and matter. Instead of using a solid mask to pattern a light beam, atom lithography patterns a beam of atoms with a "mask" made of light. Strange as this might seem, it works surprisingly well. While it is still too early to say whether atom lithography will ever be practical for chip manufacture, it boasts several features that make it worthy of further study.

Consider the diffraction problem. Atoms hardly diffract at all because their de Broglie wavelength is generally only a few picometres. Atoms are also electrically neutral, which means that a large flux can be squeezed into a small area. But how can neutral atoms expose a resist, and how can an atom beam be patterned? Research at Harvard and the National Institute of Standards and Technology in the past few years has provided answers to both of these questions. The trick lies in using a metastable rare gas such as argon.

Rare gases are unique in that they are chemically inert in the ground state, but have long-lived metastable states that can release significant energies when they strike a surface. Metastable helium atoms carry 20 eV of energy, while other rare gases provide a range of energies down to 10 eV for xenon. Once in the metastable state, quantum-mechanical selection rules forbid the atoms from releasing their energy provided that they are moving through a vacuum and are not interacting with anything else. If they strike a surface, the rules no longer hold and the energy is released. This is the basis of atom lithography. Instead of depositing photon energy in the resist, as with optical lithography, the energy of the metastable atoms is deposited in the resist.

The metastable nature of these atoms also provides the means for patterning a beam: the atoms alter the surface in certain areas, while leaving it unaffected in others. We therefore need some way to "defuse the bomb" in selected areas, releasing the energy stored in the metastable atoms to return them to the harmless ground state.

The Harvard team achieved this by using laser light tuned to an optical absorption line in the metastable atoms. When the atoms absorb light at this specific frequency, they are promoted to an even higher energy level – but only temporarily. From this level the quantum mechanics allow the atoms to relax into the ground state by emitting an ultraviolet photon. Light can therefore "quench" the metastable atoms, and a light beam containing a pattern of different intensities can impose the same pattern on a beam of metastable atoms. High-intensity regions of the light beam quench the metastable atoms into the ground state, while low-intensity regions allow the metastable atoms to pass through unaffected.

The Harvard team used a standing wave with an undulating intensity that falls to zero at integer multiples of half the laser wavelength (see figure). The wavelength was 801.5 nm, which matches a transition in metastable argon. Metastable atoms only penetrated the light field in regions very close to the zeros in intensity, since even low-intensity light was enough to eliminate all of the metastable atoms. Metastable atoms striking the surface deposit their energy in the resist, which in this case consisted of residual hydrocarbons that adhere to the substrate more strongly when struck by the energetic atoms. This formed an array of lines with a linewidth of 65 nm and periodicity of 400.7 nm.

Interesting as this new lithography technique seems, it has several obstacles to overcome before it becomes a serious contender in tackling the problem of lithography below 100 nm. For instance, it is not an easy task to pattern a beam of light in exactly the right way for printing a complex electronic circuit. Also, today's state-of-the-art metastable atom sources are pretty weak and would have to be improved to make the technique economically viable. But none of the existing contenders seems to be a clear winner for the demands of the future, so it makes sense to look for more radical approaches.