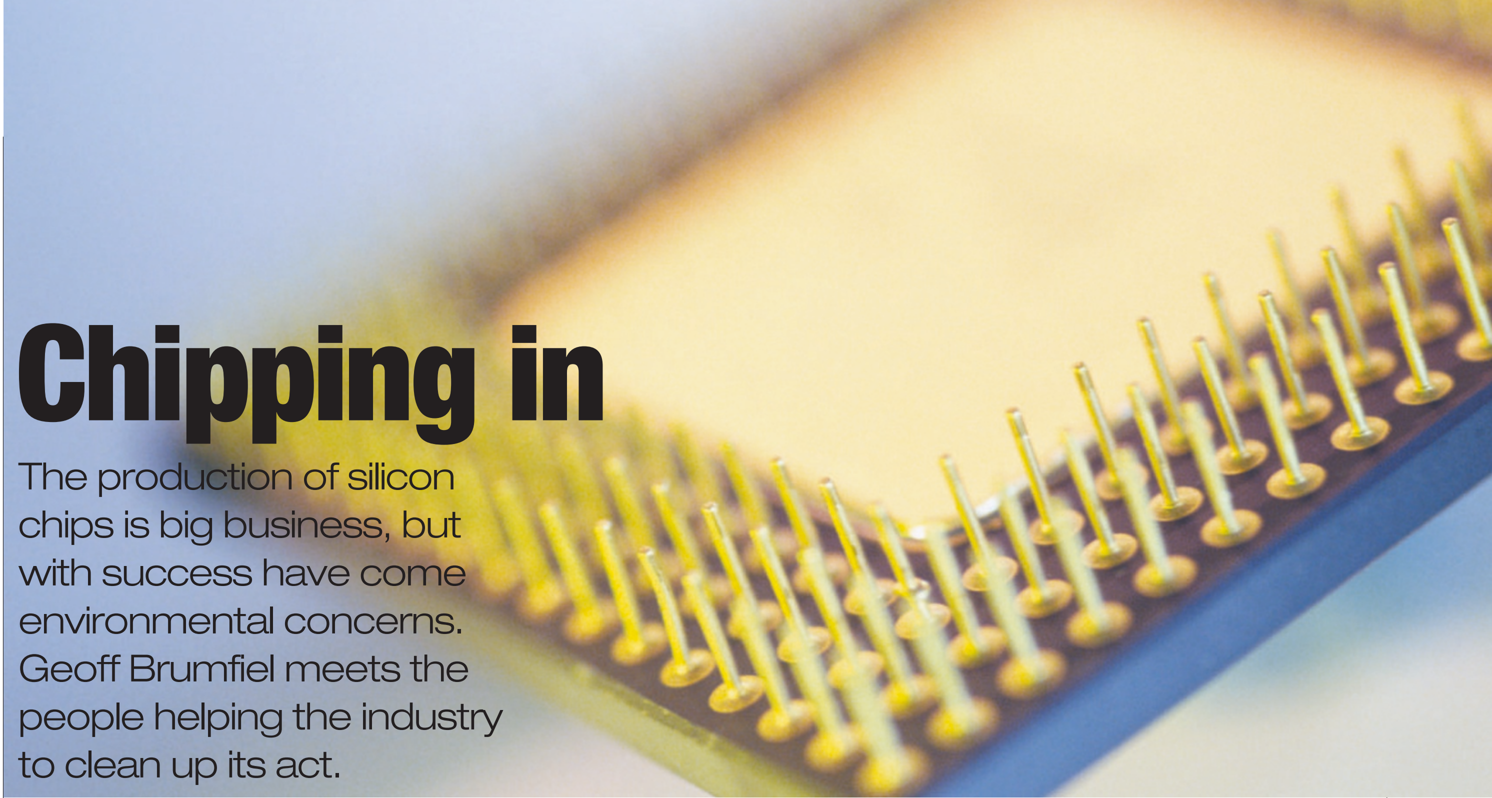

J. WILKES STUDIO/CORBIS

Chipping in

The production of silicon chips is big business, but with success have come environmental concerns. Geoff Brumfiel meets the people helping the industry to clean up its act.

On the face of it, there is nothing cleaner than a semiconductor manufacturing plant. Dust inside is kept to a few particles per cubic metre to prevent it from clogging up the micro-circuits as they are assembled. Workers wear bunny-suits to keep hair and flakes of skin from polluting the environment, and water used in manufacturing is filtered so that it is far cleaner than the water most of us drink.

But even though the working environment is pristine, it's still not exactly eco-friendly. "The reality of a fabrication plant is that it's a huge chemical factory," says Gerald Marcyk, a retired director for research at chip manufacturer Intel. Highly toxic elements, such as arsenic and phosphorus, are used to alter the electrical properties of semi-conducting materials. Volatile organic solvents are sprayed onto silicon wafers to remove waste when they are etched with circuit patterns. And the operation of a single plant consumes thousands of megawatt hours in electricity and generates millions of gallons of waste water each day.

Most environmental groups agree that semiconductor fabrication is not the dirtiest manufacturing industry, but it is one of the fastest growing — it has grown by more than 10% a year over the past few decades and currently consists of some 900 plants and hundreds of thousands of workers worldwide. Such rapid expansion has led environmentalists and the US government to turn their attention to the impact the industry is having on the environment and on the health of its employees. But in a sector that is capital- and research-intensive, changes to any working practices to make them more eco-friendly are unlikely to happen overnight.

"I think the industry is a lot more receptive than it was 20 years ago," says Ted Smith, director of the Silicon Valley Toxics Coalition, a non-profit environmental group in San Jose, California. But, he adds, more still needs to be done. According to Smith, the environmental track-record of the chip manufacturers has been less than stellar in the past. In California, where the industry originated, one in five toxic-waste sites on the US Environmental Protection Agency's list of high-priority sites waiting to be cleaned up is a current or former semiconductor plant.

The production of silicon wafers for chips consumes huge amounts of water and electricity.

S. YEH/AFP/NEWSCOM (LEFT); T. HOROWITZ/CORBIS

Health check

Worker health has also been a problem for the manufacturers. In the 1980s, solvents called glycol ethers were linked to abnormal pregnancies among female employees (M. B. Schenker *et al. Am. J. Ind. Med.* **28,** 639–659; 1995), and since 1996 hundreds of lawsuits have been filed by former employees of IBM, who claim that working in the company's facilities led them to develop cancer. IBM disputes the link with cancer, but in August the allegations led the Semiconductor Industry Association (SIA), a trade group of 95 manufacturers, to announce the largest ever cancer study covering the health records of some 200,000 former industry employees (see *Nature* **431,** 7; 2004).

Many of the problems faced by the industry are legacies of earlier technologies. But as new generations of faster computer chips are designed, companies often have to alter their manufacturing techniques, equipment and chemicals. Such changes can introduce new, and potentially unforeseen, environmental problems, but they also offer a chance to improve individual processes.

These are the challenges and opportunities that motivate Farhang Shadman, a chemical engineer at the University of Arizona in Tucson. Since 1996, Shadman has directed the Engineering Research Center for Environmentally Benign Semiconductor Manufacturing. Sponsored jointly by the National Science Foundation (NSF) and industrial partners, the centre brings together engineers, chemists and physicists from universities around the country who are working on ideas that could someday help clean up the business of making microchips. Although it receives just under \$4 million a year in funding, a fraction of the \$14 billion that SIA members spend on research and development annually, the centre has successfully transferred several technologies to manufacturers.

This year the centre's NSF funding will

R. RAHMAN/AFP/NEWSCOM

Scrubbed up: the plants may be spotless, but how environmentally friendly is the microchip industry?

expire, but Shadman is confident that industry will pick up the slack. "We will have a smooth transition from NSF funding to industry funding," he says. Reed Content, a senior environmental, safety and health manager at Advanced Micro Devices (AMD) in Sunnyvale, California, and chair of the centre's industrial advisory board, says that he is working hard to ensure it continues to receive funding next year. "I think the industry would like to see it go forward," he says.

Improving the environmental performance of a high-pace, high-tech industry requires a special way of thinking, Shadman says. Semiconductor manufacturing is a cut-throat business that over the past few years has been operating on increasingly thin margins. "Unless what we're proposing will improve performance and reduce cost, we're not going to get the industry's attention," he says.

That often means keeping the solutions as simple as possible. Shadman's own research group has been working on ways to cut water consumption at the plants. Keeping microchips ultra-clean during the manufacturing process means continually having to wash them free of chemicals.

A clean sweep

To figure out the best ways to save water, Shadman's team looked closely at how it is used. The researchers found that recycling waste water, as some have suggested, is not always the best idea because purifying it requires a lot of power. "Recycling helps the environment in one way but hurts it in another," Shadman explains.

Instead, the group focused on making water use more efficient by developing sensors that measure microchip cleanliness, and consulting on new plant designs. The team has reduced water used for rinsing in newer plants by 20–65%.

More radical changes to the manufacturing process must yield more spectacular benefits if they are to be taken seriously by industry. One such example, according to Christopher Ober, a materials scientist at Cornell University in Ithaca, New York, is the idea of replacing water with 'supercritical' carbon dioxide — a hybrid phase of CO_2 that has the properties of both a gas and a liquid.

Supercritical CO_2 forms at temperatures higher than 30 °C and at pressures of several millions of pascals. It flows like a liquid, but has negligible surface tension, giving it some serious advantages over water, Ober explains. For one thing, it can penetrate deep into microcircuitry and dissolve solvents and etching chemicals. Once it has passed through the chip and into a waste system, it reverts to being a gas, depositing whatever waste materials it dissolved. Unlike water, Ober says, this means that it can be easily recycled, and instead of creating gallons of liquid waste it leaves behind a small amount of dry waste. In addition, CO_2 is a by-product of other processes inside the plant, and so is readily available.

But supercritical CO_2 has its disadvantages as well. "The downside is that it has very complicated solubility characteristics, so not everything will dissolve in it," Ober says. This means that additional chemicals sometimes have to be added. Another problem is that plants need new tools to accommodate the process. As a result, companies have so far been reluctant to replace conventional water with supercritical CO_2. "Even though it is high-tech, the industry is still fairly conservative in terms of making changes," Ober says.

All that may now be changing for reasons that have nothing to do with the environment. As the features etched on chips reach the nanometre-scale, they become increasingly difficult to clean with water, Ober says. At such scales, the force exerted by the water's surface tension is enormous and has the potential to damage tiny circuit patterns. Because supercritical CO_2 has little surface tension, companies are starting to incorporate it into their new plant designs.

In this case, the rapidly changing technology of the manufacturing process is actually encouraging companies to be more environmentally responsible. But things rarely work out that way, so other groups with Shadman's centre are looking to influence decisions about the next generation of materials needed to make chips even smaller and faster.

"Traditionally, the microelectronics industry has worried mostly about performance," says Krishna Saraswat, an electrical engineer at Stanford University in California. "What we're now looking for are materials that give the highest performance and fewest environmental problems."

That shrinking feeling

As transistors grow ever smaller, Saraswat explains, new materials are needed to make sure that electrons do not leak from one part of the device to another. Several new compounds are being considered, but few people are worrying about their environmental consequences. Saraswat's work suggests that one class of materials — those involving the relatively benign element hafnium — are the least environmentally offensive.

But if hafnium-related materials turn out to be less effective than the others, their environmental benefits won't make them the industry's first choice. Marcyk says that the bottom line will always come first. "The reality is that people want to have an environmentally clean process, but they will not pay any more money for it," he says. "There are very few changes that I've seen that have been done strictly for the environment."

So can initiatives such as Shadman's centre really alter the course of semiconductor manufacturing? Some sceptics are less than sanguine about its chances. Smith calls the scale of the research efforts "painfully inadequate". In an industry where manufacturing techniques are constantly revised, he says, "you're always going to be playing catch up and clean up".

Supporters, on the other hand, remain upbeat about the industry's progress. Technologies suggested by the centre are making their way into plants, and young engineers entering the industry are willing to think about environmental issues. In the end, Shadman argues, the financial pressures that drive the industry will someday force all companies to think about their environmental impact. "Environmental concerns are not a luxury," he says. "It's a question of sustainability." ■

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