Nothingness might not sound very useful. In fact, the opposite is the case because nothingness – in the form of a vacuum – has played a major role in the history of electronics. Until the invention of the transistor, vacuum tubes were the industry’s critical component because they made it possible to amplify, switch and modulate electrical signals. The first computers were built using them, but they were vast and consumed large amounts of power. So, when the transistor was invented by Shockley, Bardeen and Brattain in 1947, the days of the vacuum tube as computing’s key hardware element were numbered.

But now, vacuum as a computing component could be about to make a comeback. Researchers at NASA and elsewhere are looking to use nanoscale techniques to exploit the power of the vacuum. The result is a ‘vacuum channel transistor’, which has the potential to provide dramatic improvements in efficiency, combined with the same kind of benefits that have made the transistor so successful. That is because the aim is to use manufacturing techniques similar to those developed by the mainstream semiconductor industry.

One member of the team that has created the device is Meyya Meyyappan, a researcher at the Centre for Nanotechnology at NASA’s Ames Research Centre in California. He says the project started when his research colleague Jin-Woo Han walked into his office one day and said, “You know, a vacuum is better than any semiconductor because the electrons can shoot through ballistically without getting scattered by the lattice of the silicon.”

“The thing is that vacuum tubes went away not because they were bad but because, with silicon, you could make everything so much smaller, and manufacture devices in the billions very cheaply,” Meyyappan says.

Han then said: “What if we could make the vacuum tube in a way that made it possible to produce billions of them very cheaply?”

“Actually, this was considered 20 years ago, when people tried to use microfabrication techniques and miniaturise vacuum tubes, but they did not perform that well,” Meyyappan says.

Han’s suggestion was that maybe it would be worth trying again, this time using the kind of nanoscale fabrication techniques that were not available two decades ago.
“The crucial thing is that we have to be able to make them using the semiconductor industry’s well established silicon technology,” Meyyappan says. “If you don’t do that and manufacturing becomes difficult, you will never get the vital cost benefits.”

This is what Meyyappan and Han have done, working in collaboration with Jae Sub Oh of Korea’s National Nanofab Centre. A gate insulated vacuum channel transistor was fabricated using standard silicon semiconductor processing. The vacuum transistor is created in phosphorous doped silicon by etching a tiny cavity, bordered by three electrodes: a source, a gate, and a drain. The source and drain are separated by 150nm, with the gate on top. Electrons are emitted from the source, thanks to a voltage applied across it and the drain, while the gate controls the electron flow across the cavity.

Advantages of the vacuum tube and transistor are combined here by nanofabrication. A photoresist ashing technique enabled the nanogap separation of the emitter and the collector, thus allowing operation at less than 10V.

“Nanoscale vacuum tubes can provide high frequency and power output while satisfying the metrics of lightness, cost, lifetime, and stability at harsh conditions, and the operation voltage can be decreased comparable to modern semiconductor devices,” the researchers say.

“Everything is done using silicon based technology – a conventional source and drain, standard optical lithography together with the technique of plasma ashing to create a nanogap separation of around 150nm between the emitter and collector,” Meyyappan says.

The first device produced by the team achieved a performance of 460GHz. “Our point is that you can potentially make these devices with a much smaller gap – 10 or 20nm – and if you do, the performance will increase and the operating voltage – now between 7 to 10V – will scale right down to 2V or so.

“Even though we call it a miniaturised vacuum tube, unlike the big old versions, you don’t have to start using pumps to suck out air to create the vacuum. The principle is there should not be any collision between the electrons and the air. When the gap between the source and drain is of the order of 150nm, the mean free path of the electrons (the average length an electron can travel before hitting something) is more than 1µm, so the electrons do not collide. It’s like the vacuum is given to you for free.”

Technology with future potential

The work done by the NASA team started less than a year ago and their hope is that it will attract interest from the semiconductor community and potential manufacturers.

“We can go on ourselves, for example, by further reducing the gap, to show increased performance, say up to 600GHz and beyond, and also reducing the operating voltage. But NASA is not a volume manufacturing company, so a partner will be needed. But companies can do it by themselves if they wish to.”

Meyyappan sees the vacuum channel transistor as a potential candidate for the future of electronics. “It’s recognised that we have a few generations of standard silicon development left, but there is a question as to how we are going to keep progress going beyond that. People have talked about things like carbon nanotubes and graphene, but they just don’t look like they are going to provide what we need – at least in the right time frame.

“For carbon nanotubes, what kind of infrastructure do you need to make billions of them, and who is going to do it? For the semiconductor industry, which is very conservative, carbon is still an exotic material.”

This is why Meyyappan sees it as so important that there is no problem...
Cover Story Vacuum Technology

creating the vacuum transistor on a standard silicon platform, using exactly the same fabrication processes.

There are other potential applications. For example, once you reach the terahertz regime, the applications that become possible are already well known, from spectroscopy to security scanning, medical imaging, communications and astronomy. Terahertz devices made in their millions, with all the cost savings that ensue, could generate huge new markets.

“The current-voltage characteristics of a vacuum transistor based system would look different to today’s conventional silicon mos, given that silicon acts as a conductor. With vacuum systems, the electrons travel through ballistically in a way similar to a fast tunnelling process,” Meyyappan says. “But you would still be able to put together circuit components to build conventional elements like AND or NAND circuits, just as we have done for decades, to create vacuum based ics.”

Balistic conduction — the transport of electrons in a medium with negligible electrical resistivity due to scattering — is what makes the use of the vacuum so potentially significant. Another researcher looking to exploit ballistic transport is Professor Hong Koo Kim of the University of Pittsburgh. Typically, he says, it is difficult to achieve ballistic transport in a solid state medium because the high electric fields used to increase the carrier velocity also increase scattering.

“Vacuum is an ideal medium for ballistic transport, but vacuum electronic devices commonly suffer from low emission currents and high operating voltages.”

Prof Kim and his team have shown that electrons trapped inside a semiconductor at the interface with an oxide or metal layer can be easily extracted out into the air. The electrons at the interface form a sheet of charges, which is termed a two dimensional electron gas. Kim has demonstrated that the Coulombic repulsion — the repulsive force between two positive or negative charges as described by Coulomb’s Law — in the electron layer makes possible the easy emission of electrons out of silicon. The team extracted electrons from the silicon structure efficiently by applying a negligible amount of voltage and then placed them in the air, allowing them to travel ballistically in a nanometre scale channel without any collisions or scattering.

“The emission of this electron system into vacuum channels could enable a new class of low power, high speed transistors and it’s also compatible with current silicon electronics, complementing those electronics by adding new functions that are faster and more energy efficient due to the low voltage,” Prof Kim says.

It will certainly be a major innovation if vacuum based transistors become widely used as computing components by the IT industry. But in many other electronic applications, the use of the vacuum never went away.

“Far from disappearing as a result of the introduction of solid state electronics, vacuum pumping technology today plays a key supporting role in at least 70 general manufacturing applications, spanning a wide range of industries,” says Stephen Ormrod, chief technology officer at Edwards, the Crawley based manufacturer of vacuum pumps and abatement technology, which has been in the business for nearly 100 years.

“The semiconductor, flat panel display, solar manufacturing and scientific instrumentation industries have driven recent developments in vacuum technology and are likely to continue to do so in the future. Vacuum process technology is alive and well and solid state electronics has become the technology’s biggest driver.”

“All the main steps in growing and connecting transistors on a silicon wafer to form a memory or logic chip are enabled by vacuum,” adds Mike Percy, general manager of Semicon Vacuum Pumps at Edwards. “These include depositing layers by chemical vapour deposition and atomic layer deposition to form transistors and capacitors and etching patterns, and filling with copper or aluminium by physical vapour deposition to form the interconnecting wiring.”

Two particular advances in semiconductor technology — lithography and increasing wafer size — are posing major challenges for the vacuum techniques they require.

“The industry is now at the point where it needs to use extreme ultraviolet [euv] light with a wavelength of 13nm to image dimensions of less than 15nm,” Percy says. “For these next generation lithography tools, the whole process of generating the euv light, focusing it and imaging the wafer surface needs to take place in vacuum.”

Lithography tools are the biggest, most expensive and most complex process tools in a semiconductor fabrication plant and the switch to making these vacuum tools is a huge endeavour, one which Edwards has been working with the leading toolmaker on for more than a decade.

“Over the next few years, the semiconductor industry will see wafer size increasing from 300mm to 450mm,” Percy explains. “This will require a scaling up, in the size and types of tools that will be necessary to enable this to happen. The development will bring with it a wide range of vacuum challenges, not least the substantial increase in the volumes and flowrates within the process chamber itself.”

Overall, advances in vacuum technology of the kind made by Edwards have a major impact on semiconductor processing, he says. “A state of the art semiconductor factory would save approximately half of its vacuum running costs using latest generation vacuum pumps compared to first generation pumps, equating to several million dollars a year.”

Clearly, nothingness was never more valuable.