THE ROYAL SOCIETY

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Royal Society submission to the House of Lords Science and Technology Committee Inquiry – Innovations in microprocessing

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This submission has been produced by a working group chaired by Professor John Enderby CBE FRS (Physical Secretary and Vice President, Royal Society). The membership of working group is given at the end of the submission. The Council of the Royal Society has endorsed this submission.

This submission is in response to the call for evidence by Sub Committee II of the Science and Technology Committee of the House of Lords, chaired by Lord Wade of Chorlton, as part of the inquiry into innovations in microprocessing[1]. The Sub Committee is investigating whether microprocessor technology will be able to continue to meet the demand for ever increasing computing speed. The submission responds to the four questions outlined in the Sub Committee's call for evidence.

Summary of key points

- The demands for increased computing speeds will continue due to the large number of new and existing applications.
- As microprocessing power has increased the number of components per chip has increased, forcing each component to become smaller. There is a lower size limit for components below which the existing technologies will not be able to operate that will halt the increase in microprocessor speed.
- Microprocessor speed is only one factor in overall computer speed and the other factors, such as software design and chip architecture, could be exploited to maintain increasing computing speeds.
- There are unlikely to be any mainstream non-silicon semiconductor technologies to compete with modified versions of existing silicon-based semiconductors to deliver the desired processing power during the next 20 years. However, there may be niche market technologies within this timescale.
- The longer-term options are currently areas of scientific research and will require co-ordination and long-term funding in order to exploit their potential development into fully-fledged technologies. These options may develop from current research in the broad areas of quantum computing and nanoscience and, if adequately funded, might deliver by 2015 and beyond.

Recommendations

- The formation of a limited number of centres of excellence to concentrate the areas of current UK expertise and provide access to world-class facilities. These centres would also act as technology nodes.
- The Government should establish an initiative to co-ordinate UK expertise, agree a strategy between academics and industrialists, and provide adequate funding.
- Continued funding of a diverse science base to ensure supporting technologies are available.
- Further Government measures to stimulate innovation by entrepreneurs.

What are the main drivers for increasing computer speed? Is there any reason to expect that the demand for increasing speed will abate?

Microprocessor speed can be defined as the speed at which the microprocessor executes instructions. This is only one of many factors that determine the overall computing speed. Other factors include the architecture of the individual components on each silicon chip, the interconnections between components within computers, connections between computers and networks, and software. Most consumers want faster overall speed, which has been mostly delivered through increasing microprocessing power. However, many current computer users are limited by the speed of their Internet connection rather than the microprocessor speed.

There are many drivers for increasing computer speed, including:

- the intrinsic complexity of many scientific and technological problems, examples are weather forecasting, computational chemistry and aircraft design.
- the demand for increasingly data-rich home and mobile entertainment, an example being able to store an entire film on a single silicon chip.
- the demand for increasingly data-rich home and mobile communication, for example videophones.
- the challenges of artificial intelligence, examples being developing better human-machine interfaces, intelligent and adaptable expert systems or versatile robots.

As the technology becomes available for increased computing speed novel uses will be found.

What are the physical limits to the speed of processing based on present techniques? When are these limits likely to be reached?

With the current silicon-based integrated circuits (or 'silicon chips' as they are often referred to), microprocessor speed is based on the number of components per chip. In order to increase the microprocessor speed without increasing the size of the integrated circuit each component needs to become smaller. There are a number of problems as component size decreases and these are outlined below.

- Current integrated circuits contain a silicon layer that has other atoms added (known as dopants) to give the layer the required electrical properties, making it a semiconductor. The basic building block of an integrated circuit is a gate, which performs logical operations in binary. As the gate length decreases the number of dopant atoms drops leading to a poor distribution: with too few dopant atoms a gate will not have the required semiconducting properties to operate as the potential drop will no longer be smooth. This leads to a currently perceived 'brick wall' that gates below 70 nanometers are not feasible.
- There is a physical lower size limit for the existing silicon based integrated circuits due to the thickness of the silicon layer and the gate length[2]. The size limit of 1.5 nanometers is the minimum thickness of a silicon layer that will have the necessary electrical properties: below this size too much current is lost due to electron tunneling.
- As the individual components on integrated circuits get smaller there are increasing difficulties with heat dissipation, as the power is generated in ever decreasing areas.
- Interconnects between components on chips currently account for 70% of their area and are responsible for an equivalent proportion of the defects[3]. As the components get smaller, interconnects will become occupy a greater area and consequently be an even greater cause of defects. Also, as the interconnects themselves become smaller there will be increasing problems with surface resistance.

These issues have been addressed by a series of roadmaps produced by the semiconductor industry, the most recent of which is the International Technology Roadmap for Silicon: 2001[4] (ITRS) produced by experts from Europe, Japan, Korea, Taiwan and USA.

In 1965 it was proposed that the number of components per chip doubles every 18 months[5]. This proposal has become known as Moore's law, after Gordon Moore who went on to co-found Intel in 1968. The semiconductor industry has been operating according to Moore's law and has used the increasing number of components per chip as the main way of increasing overall computing speed. However, there are predictions that this will cease to hold between 2010 and 2018[3]. Although the actual date that this law will cease to hold for the existing silicon-based semiconductor technology is uncertain, it is certain that it will cease to hold although new developments might postpone this.

The limits to processing speeds are not just physical: there are economic constraints. It may be possible to produce faster speeds based on existing technologies but their fabrication will not be economically viable. Since 1965 there has been a trend in the cost of production: the cost-per-chip has doubled every six years[6]. Current estimates are that the production cost-per-chip will start to increase more rapidly by 2010. The growth of the semiconductor industry relied on the predictable increase in production costs and more rapidly increasing production costs would have a serious impact on the semiconductor industry.

What are the most promising alternative techniques and technologies for achieving ever greater processing speeds over the next 15 to 20 years? What expertise does the United Kingdom have relevant to these?

Silicon-based semiconductor technologies are likely to provide the only practical mainstream option for delivering the desired processing speeds in the next twenty years. However, there are potential developments based on or involving silicon and details are given below.

There is no evidence that post-silicon technologies will be sufficiently developed to provide a significant alternative but they may be able to contribute to niche markets. Due to the enormity of the computer processing business 'niche' markets could be quite significant. In order to replace silicon-based semiconductor technology in mainstream microprocessors any new material will need to be cheaper and easier to produce than silicon-based semiconductors of equivalent processor speeds.

The UK possesses great strength in supporting technologies required for any future technology.

Silicon-based semiconductor technologies

Three possibilities for silicon semiconductor-based technologies beyond 2020 are devices such as single electron transistors (SETs), spin resonance transistor (SRTs) and self-assembled quantum dots (QDs). These all require the ability to manipulate single particles (atoms and electrons) for both their fabrication and operation and the latter two (SRTs and QDs) are really aimed at quantum computing.

Single electron transistors have been studied for a number of years and have revealed some fascinating physics[7] but difficulties associated with the low power output and high noise levels have meant that this is not a practical technology for microprocessors. However, this research may provide a lead to a novel technologies based on a small number of electrons. The UK is probably a world-leader in this area as a result of the work initially funded by the Science and Engineering Research Council (SERC), then later by Hitachi.

Spin resonance transistors can be based on either nuclear or electron spin effects[8]. Although the physical principles appear sound, the fabrication of the nuclear spin version will be extremely difficult. Due to the problems associated with the need for high spatial control and positioning of atoms nothing has yet been demonstrated. The electron spin based device may be simpler to fabricate, as electron spins are easier to manipulate than nuclear spins, but it still represents a major challenge and has not yet been demonstrated in any form. The majority of research in this area is currently being undertaken in Australia and USA.

The most advanced concept in terms of fabrication is the use of self-assembled quantum dots[9] (QDs), but there are major difficulties both in achieving an adequate degree of control over their size and composition uniformity and in implementing them in any computing device. A major study of quantum dot growth mechanisms would be required before QDs could become a viable technology. This study would need to establish the distribution and reproducibility of formation, together with a serious effort directed at their optical and electronic properties to find how best they might be exploited. QDs have the potential to be used both in silicon and on their own. There is UK expertise in QD research.

As individual components in silicon-based semiconductors become smaller, quantum effects will become increasingly important. The theory and practice of controlling and correcting errors in quantum systems, currently being developed as part of quantum information science and technology, might help to prolong the useful life of existing technologies and extend the timescale over which Moore's Law holds. If so, the UK's strong theoretical and developing experimental expertise in quantum information science will have significant practical impact on mainstream microprocessing within the next decade or so.

Post-silicon technologies

Today, there is a considerable amount of research in a number of areas that could potentially lead to a post-silicon technology. Some of these areas of research will inevitably fail to deliver, and some will provide different, unexpected applications. There may also be areas of research that unexpectedly deliver an appropriate technology. This current situation is similar to that of the 1930s: during the thirties there was fundamental research into semiconductors being undertaken that laid foundations the semiconductor industry only began to exploit in the 1960s and 1970s.

These longer-term options will require co-ordination and long-term funding in order to exploit their potential development into fully-fledged technologies. These options may develop from current research and, if adequately funded, might deliver by 2015 and beyond.

The main aim of these research areas is to address the limitations of the present technologies and will be based on the manipulation of single particles (either electrons or atoms). Specific examples of areas of current scientific research that the UK has expertise in are listed below.

- Quantum computing: a quantum bit (or qubit) has the potential to have 2^n states in contrast to a classical bit that can only have 2n states. However, there are currently discussions about the possibility of producing a hundred qubit-based system in the next decade. The breadth of research expertise in this field will be illustrated at a two-day discussion meeting being held at the Royal Society 'Practical realisations of quantum information processing' on 13 and 14 November 2002.
- Nanotechnology: this is an enormous area that covers a number of potentially useful technologies. One of many possible examples is carbon-based electronics. This could avoid or reduce the problems associated with heat dissipation. Organic semiconductors and consequently plastic electronics have the potential to provide cheap, rugged and lightweight electronic devices. This would make wearable or even disposable computing a possibility[10], applications that silicon-based semiconductors could not easily be used for.
- Optical signal processing: preliminary investigations are being undertaken.

Further technical details of these technologies are given in the *Technology Roadmap for Nanoelectronics* produced by the Microelectronics Advanced Research Initiative of the European Commission's IST programme on Future and Emerging Technologies[11].

Supporting technologies

There are a number of supporting technologies that will be important in the development of any future technologies. The UK expertise in metrology will need to be maintained in order for adequate inspection, measurement and quality control to take place. Similarly, the current UK skill base in specific areas of lithography such as X-ray optics and production and high-resolution electron beam systems will be important in the fabrication of any new technology. There is great expertise in advanced semiconductor growth and equipment manufacture. However, the research in silicon technology is not internationally competitive and without appropriate funding this would hinder the development of novel silicon-based systems.

The UK was a pioneer of quantum information science. Among other achievements, UK-based theorists were among the first to recognise the qualitatively distinct nature of quantum computing, to develop quantum algorithms more efficient than their classical counterparts, and to develop secure quantum cryptographic schemes. The UK remains very strong in quantum information theory, and has strong experimental expertise in some of the areas of application.

Are there significant rôles for the United Kingdom in future developments? What international collaborations would be beneficial? What actions should be taken by the Government (through innovation policies and otherwise), publicly-funded research bodies and the private sector?

The UK can have a rôle in the future developments as outlined above but there are a number of obstacles to realising this. The problem facing the United Kingdom is not a lack of talent, rather a lack of focus and coordination for the existing talent. The challenge is to ensure that the UK's diverse expertise is organised and has access to appropriate facilities. It is also essential to maintain the funding for fundamental scientific research continues to be funded, as this will continue to feed into novel technologies as they develop.

We believe that the co-ordination of expertise can be best achieved by concentrating funding on a limited number of centres of excellence rather than spreading the funding over a greater number of research establishments. This allows sufficient funding for researchers to have access to world-class facilities. One such centre of excellence should focus on research and development of novel silicon-based semiconductor quantum computing structures. With adequate funding this centre would be able to deliver both the science and technology.
Recommendation: the formation of four to five centres of excellence to concentrate the areas of current UK expertise and provide access to world-class facilities.

A highly successful example of a UK Government funded programme was the eight year Science and Engineering Research Council (SERC) *Low Dimensional Structures* (LDS) initiative set up in 1985, that helped establish the UK as an international leader in the field. LDS produced both excellent science and benefits that are still being felt in the scientific and technological community today. For example, the opto-electronic industry grew directly out of the initiative through the formation of a number of spin-off companies, which was not the case during the 1980s. There were two key factors in the success of the LDS initiative: academics and industrialists agreed a strategy together and sufficient funding was provided to allow advanced technology in the participating laboratories. Both of these would need to be repeated in any future initiative.
Recommendation: the Government should establish an initiative to co-ordinate UK expertise, agree a strategy between academics and industrialists, and provide adequate funding.

In any future initiative funding should go directly to individuals or groups who put forward a valid case, rather than institutions. Such an initiative would benefit from having a single person, possibly appointed by the Research Councils, to co-ordinate: similar to the current role of the EPSRC Director of e-Science.

Specific initiatives would have the added advantage of promoting new developments in related areas. For example, focused research into advanced semiconductor growth and processing would cause new developments in a number of related areas of semiconductor physics, such as metrology and lithography.

In addition to focussed specific initiatives, it is essential that a broad range of fundamental research be maintained at an appropriate level. Such research is vital to future supporting technologies and the techniques required to develop them.
Recommendation: continued funding of a diverse science base to ensure supporting technologies are available.

Once the UK has established its expertise in particular areas with well-defined intellectual property rights, it would be beneficial to engage in international collaborations as the UK is not going to be able to single-handedly undertake all of the necessary research to fully develop these technologies. Collaborations with other EU nations and the Australians could be advantageous at this stage.

The success of the UK in future developments is not solely dependent on co-ordinated funding of existing research talent: the economic conditions for UK spin-off companies compared to international equivalent organisations will be a considerable factor. These issues have been addressed in Sir Peter Williams report to the Treasury[12] on high technology businesses. The Royal Society welcomes the extension of R&D tax credits to large companies[13] as announced by the Chancellor in his March 2002 Pre Budget Report. We would recommend further measures to stimulate innovation by entrepreneurs such as greater concessions for capital gains tax for start-up businesses, the increased availability of seed funds and assistance in providing protection for intellectual property rights.
Recommendation: Further Government measures to stimulate innovation by entrepreneurs.

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