ABSTRACT
Low power technology is impacting our society by creating the newly emerging digital consumer market, which leads to the nomadic life-style. In this paper, historical review of the technologies will be provided with some examples. It is suggested that robotics will provide the major challenge for low power electronics in the coming decades.

Categories and Subject Descriptors
B.37.0 [Integrated Circuits]: General

General Terms
Design

Keywords
Low power technologies, Nomadic Age, Applications, Robotics.

1. INTRODUCTION
New trends in lifestyle in the ubiquitous society, which could be called as nomadic style, are wide spreading these days thanks to the rapid progress in microelectronics technology [1]. People are becoming more and more connected through communication networks and intelligent electronic terminals wherever they may be. Nomadic life style in the ubiquitous society will be more common as the constraints of time and location are broken. The low power electronics will play a key role in this nomadic age. Rather than describe and discuss the technical details of LSI chips, this paper will provide a broader and more historic view of the impact of the evolution of low power electronics and its future applications [2].

2. Figure of Merit in the Nomadic Age
Progress in semiconductor technology has led to smaller and lighter electronic devices. The trend in several such devices is illustrated in Fig. 1.

The first notable example is the electronic calculator, the size of which was reduced roughly three orders of magnitude in ten years. This drastic change was made possible by reducing the number of chips used. Electronic calculators initially used several thousands of transistors and diodes. The next generation used several tens of integrated circuits.

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The great success of i-mode cellular phone in Japan suggests the new development in this direction.

The basic requirements for such nomadic tools, summarized in Fig. 2, led to the formulation of a “figure of merit” for the nomadic age [3]:

\[
\text{Figure of Merit} = \frac{\text{(Intelligence)}}{\text{(Size)} \times \text{(Cost)} \times \text{(Power)}}
\]

The ideal nomadic tool will be designed in such a way that it has more intelligence in smaller space at lower cost and at lower power. Reducing power dissipation is of primary importance in the nomadic age so as to achieve a longer battery life. This is to indicate the new direction of low power electronics in the new century, which is different from the PC-centric age in the past decade.

3. Historical Review of Low Power Technology

Since power dissipation is proportional to the square of the supply voltage, great efforts have been made to reduce the supply voltage. The trend in the supply voltage of semiconductor devices is shown in Fig. 4. A power supply of 24 volts was used in early devices in the 1960s. It was standardized at 5 volts in the mid 1970s, and 5 volts remained the most widely used supply voltage until the early 1990s. As the minimum feature size shrinks to the deep sub-micron range, the supply voltage has dropped to as low as 1.5 to 1.8 V. According to the 2002 ITRS, or International Technology Roadmap for Semiconductors, issued by the Semiconductor Industry Association [4], the supply voltage is expected be 1.2 to 0.9 V in 2005 and 1.0 to 0.6 V in 2010.

In 1981, Hitachi applied the same CMOS technology to an 8-bit microprocessor. As shown in Table 2 comparing to its NMOS counterpart, it was twice as fast, and its power dissipation was 1/30 in active mode and 1/7,000 in standby mode. It also contributed for setting the new direction of technology for microprocessors and logic devices.

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Table 1. NMOS vs. CMOS for SRAM

<table>
<thead>
<tr>
<th>Product</th>
<th>Technology</th>
<th>Speed</th>
<th>Active/Standby</th>
<th>Chip Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>2147(1977)/Intel</td>
<td>NMOS 4Kb</td>
<td>55 / 70 ns</td>
<td>110 mA / 15 mA</td>
<td>16.2 mm²</td>
</tr>
<tr>
<td>6147(1978)/Hitachi</td>
<td>HiCMOS 4Kb</td>
<td>55 / 70 ns</td>
<td>15 mA / 0.001 mA</td>
<td>11.5 mm²</td>
</tr>
</tbody>
</table>

Table 2. NMOS vs. CMOS Microprocessor

<table>
<thead>
<tr>
<th>Product</th>
<th>Technology</th>
<th>Speed</th>
<th>Power</th>
<th>Pin Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>680(1979)/Hitachi</td>
<td>4 micron NMOS</td>
<td>1MHz</td>
<td>900 mW</td>
<td>40 pins</td>
</tr>
<tr>
<td>6301(1981)/Hitachi</td>
<td>3 micron CMOS</td>
<td>1/1.5/2MHz</td>
<td>30 mW (f=1MHz)</td>
<td>40 pins</td>
</tr>
</tbody>
</table>

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Figure 5 summarizes the history of semiconductor device structures. Simply stated, the past 30 years have been dominated by CMOS convergence. The original CMOS device developed by RCA was applied primarily to low-power devices, such as electronic watches, for which speed was not an issue. The next big market for CMOS devices was calculators with liquid-crystal displays, which also did not require high speed.

Hitachi’s introduction of high-speed CMOS SRAM, 6147 in the late 1970s was the start of CMOS convergence for almost all types of products. In the 1980s, flash memory and DRAM shifted from NMOS to CMOS. The final step in CMOS convergence came in the 1990s, when servers and mainframes shifted from bipolar ECL/Bi-CMOS to CMOS. It is quite likely that CMOS will remain in the main stream of device structures for many years to come.
4. Innovations in Architecture

The architectural innovations are also important for realizing the low power chips. The mainstream architecture of MPUs has been CISC because the majority of PCs was based on Intel’s architecture. In the late 1980s, the RISC architecture was introduced; it was applied mainly to high-end machines such as workstations and servers. In the 1990’s, re-engineering of the RISC architecture led to higher performance per unit of power, i.e., higher value of MIPS/Watt. ARM was the first product in this direction, and today, there are various architectures such as MIPS and SH in this category.

Figure 6 shows the distribution of MIPS vs. Watt for various types of processor architectures. The new generation RISC machines are far superior to the traditional CISC/RISC machines used for PCs and workstations in terms of MIPS/Watt. The power dissipation of new generation RISC micro is designed to be one or two watts or less, so that the chip can be packaged in less expensive plastic package. The net result is much improved cost effectiveness in terms of MIPS/cost. This is the main reason the new generation RISC machines are gaining in popularity for newly emerging digital consumer products.

Innovation in processor architecture is still proceeding, including the recent development of the Crusoe chip from Transmeta, which is based on an entirely new software approach and will greatly impact the direction of low power electronics.

Figure 7. Schematic diagram of reconfigurable circuits

Sony's latest network walkman integrates re-configurable logic block as its audio codec engine, with the name of "Virtual Mobile Engine™". The features are shown in Fig. 8. This is the first dynamic re-configurable engine implemented in a consumer electronic product. Comparing with the DSP based system, the new device operates at 1/4 of power dissipation.

5. SoC and Emerging Markets

The “system on a chip”, or SoC, will be a powerful way of achieving a low power and high performance chip. Figure 9 shows an example of SoC, a 3-D graphic chip, in which an 8Mb DRAM is integrated on a chip. When it was integrated into a single chip, the performance improved four times and the power dissipation dropped to one-fifth. These improvements are typical when shifting to a SoC from a system on board. Because of these great benefits, there will be a steady shift toward SoC, which will in turn promote the emerging market for digital consumer products, which require high performance, low power, and low cost.
Fig. 10 shows the trend in the semiconductor market for the Digital Consumer (DC) segment in comparison with the PC market. Mobile phones have the largest share of the DC segment today. However, various types of other products, including digital TV, game machines, DVD, digital cameras and in-car navigation systems, are also gaining momentum.

The implication of the emerging DC market is that there will be a shift in the engine propelling the semiconductor market and technology, namely from PC to DC. Of course, this does not mean that the PC will disappear. However, the dominant role it played in the electronics industry during the last two decades will diminish, and it will be supplanted by DC products connected via communication networks. The low power electronics will be the most critical factor for succeeding in the emerging DC market.

Fig. 11 is to show the evolution of robot intelligence [6]. Generally speaking, the intelligence of today’s robot is far inferior to human intelligence, especially in the fields of pattern recognition and language understanding.

However, robot intelligence will dramatically increase in the coming decades, owing primarily to the progress of high performance and low power chip technologies. Fig. 11 shows a prediction of robot intelligence by Dr. Moravec of Carnegie Mellon University [6]. Of course, it is not a simple issue to compare intelligence between a robot and a human, but this figure may give a kind of feeling of how the robot’s intelligence will continue to rise. The robot will provide the biggest challenges for the low power electronics in the future, since the total power consumption is very limited in the range of several watts to several tens of watts. Therefore, it is required to achieve very high value like $10^6$ to $10^7$ in terms of MIPS/Watt. How to achieve such figures of high target in the coming decades? That remains the major challenge for low power electronics.

8. REFERENCES