Electronics Beyond Nano-scale CMOS

Shekhar Borkar
Microprocessor Technology Lab, JF2-04, 2111 NE 25th Ave, Hillsboro, OR 97124.
Shekhar.Y.Borkar@intel.com

ABSTRACT
This paper presents nano-scale CMOS outlook, discusses the three tenets that have made electronics successful in the past, and using these tenets conclude that there is nothing on the horizon yet that has promise to replace CMOS. Therefore, we will make CMOS work for a foreseeable future.

Categories and Subject Descriptors
B.7.1 *Microprocessors and microcomputers, VLSI.*

General Terms
CMOS, Design, Variations, Performance, Reliability.

Keywords: CMOS, Power, Nano, Variability.

1. Introduction
Electronics has evolved tremendously in the last century. In the early days, switches and electro-magnetic relays were used as primitive logic gates for control. They were much faster and reliable than mechanical devices. Since then, the evolution has been relentless: relays replaced by vacuum tubes, and subsequently by discrete bipolar transistors. The advent of integrated circuits added another dimension of compactness and reliability. MOS transistors were electronically inferior compared to their bipolar counterparts, but were integration friendly, and hence became the corner-stone of Moore's Law (doubling of transistors every two years). CMOS was on the horizon then, but was considered exotic and expensive, offered low power but lower performance too; it found use mostly in battery operated devices such as watches. But later it replaced plain (N and P) MOS due to improved circuit robustness and reduced power, and it has lasted for a long time (thirty years!).

CMOS has now scaled down into nano-scale regime. Where is CMOS going, and what comes after it? To address these questions, first let's look at where CMOS is headed.

2. CMOS Outlook
Table 1 shows CMOS technology outlook extrapolated from the trends that we see today. Notice that today's nano-scale CMOS is at 65nm node, where the transistor channel lengths are even smaller, of the order of 35nm. As the technology scales every two years, the transistor integration capacity doubles (Moore's Law), gate delay reduces by 30%, energy per logic operation reduces by 65%, and power consumption reduces by 50% [1].

High Volume Manufacturing	2006	2008	2010	2012	2014	2016	2018
Technology Node (nm)	65	45	32	22	16	11	8
Integration Capacity (BT)	4	8	16	32	64	128	256
Delay = CV/I scaling	~0.7	>0.7	Delay scaling will slow down				
Energy/Logic Op scaling	>0.5	>0.5	Energy scaling will slow down				
Variability	Medium		High			Very High	

Table 1

Transistor threshold voltages have reduced to the extent that subthreshold leakage power has become excessive, and therefore expect supply voltage and threshold voltage scaling to slow down in the future, resulting in lower energy, power, and delay reduction.

Random dopant fluctuations and sub-wavelength lithography will result in higher static variations, supply voltage and temperature variations will cause dynamic variations, and the variability in general will continue to become worse [2]. Higher electric fields will worsen transistor reliability and degradation. Total transistors on a chip will continue to double every two years; however, due to variability and degradation, design will be challenging, shifting to designing a system with billions of unreliable components [3].

How far will this continue, and what comes after nano-scale CMOS? To answer this question, let's look at why electronics evolution in the past was successful.

3. The Three Tenets
Electronics evolution was successful because it followed the three tenets: (1) Gain, (2) Signal to noise, and (3) Scalability. Evaluate electronic components, both past and present, against these three tenets and notice that all of them followed these tenets, without exception.

Gain: Even an electro-magnetic relay has current gain; it switches higher current than the current flowing through the coil. Vacuum tubes, bipolar transistors, and MOS all exhibit voltage or current gain.

Signal to noise: Electronic circuits built with relays, vacuum tubes, bipolar transistors, and MOS all create signals that are higher than the noise floor. That is, you don't have to hunt for a signal in the noise at the operating temperature.

Scalability: Scalability in some shape or form is essential. It does not mean dimension scaling alone as in the case of MOS transistors. For example, relays scaled in size and energy, from large relays to small, vacuum tubes scaled to miniature sizes, bipolar transistor, and MOS integrated circuits all exhibit scaling property.

Gain allows you to build circuits with increasing signal strength, and makes logic fan out possible. A single logic gate must drive more logic gates to realize a logic function, and voltage or current gain is essential. Without gain it may be possible to build memory (storage) circuits, but not logic.

Signals must have sufficient energy to distinguish from background noise, otherwise you will have to hunt for signal in the noise, spending more energy. Scalability allows you to pack more electronics, provides higher performance, lower energy and power, all at lower cost. Thus providing more and move value with each generation for reduced cost.

4. Evaluation

Let us evaluate how electronics has adhered to these three tenets and provided the value that we enjoy today.

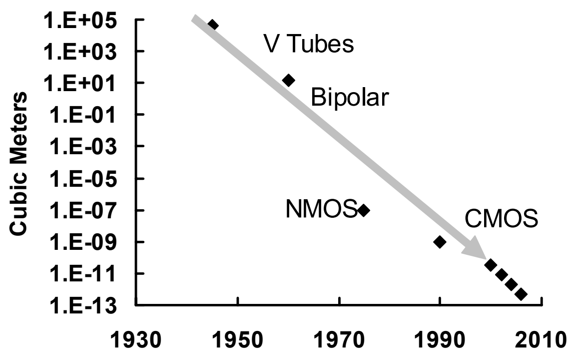

Figure 1: Dimension scaling

Figure 1 shows scaling of size over the years. Vacuum tubes, bipolar transistors, and MOS transistors followed dimension scaling, improving density, and thus reducing cost.

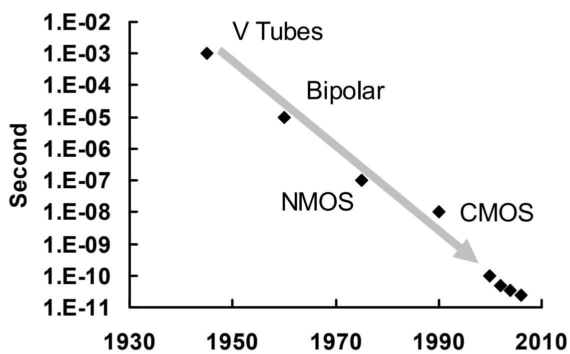

Figure 2: Delay scaling

Figure 2 shows scaling of gate delay over time, starting from vacuum tubes to today's CMOS. Gate delay has reduced from mili-seconds to now pico-seconds, improving performance by orders of magnitude.

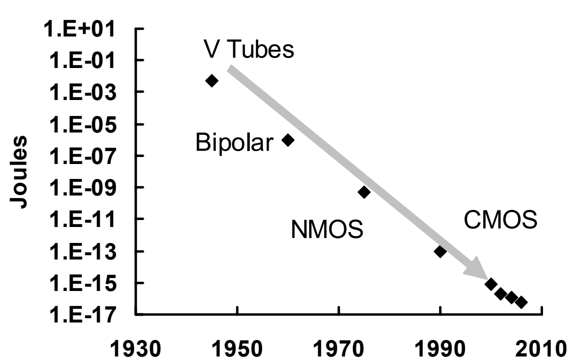

Figure 3: Energy per logic operation

Figure 3 shows how energy per logic operation has scaled down to keep power dissipation within limit.

Notice that throughout electronic evolution in the last century the three tenets were followed, consequently the integration capacity increased, performance improved, and energy (power) reduced, thus continually providing more end user value with lower cost.

5. What is after CMOS?

Any technology that will replace CMOS must follow the three tenets and continue to provide higher end user value with lower cost. Is there anything in sight that meets these tenets?

Carbon Nano-Tubes and compound semiconductors look somewhat promising to replace today's silicon based CMOS. These technologies may meet some of the tenets, and some of them have potential. After all, these technologies will replace silicon with some other material in the MOS transistor, but will still be CMOS.

We also hear a lot of reports regarding advances in Quantum, Optical, Biological, and Chemical devices as a potential solution beyond nano-scale CMOS [4]. In some cases these technologies have been demonstrated at a much smaller level, such as a logic gate or a single bit memory. To realize these technologies in practice, however, they must follow the three tenets, have to mature, and still retain the benefit. So far, we have not seen any technologies that follow these tenets; let alone waiting for them to mature. All of these technologies show no gain, operate at cryogenic temperatures with poor signal to noise ratio, hence impractical to build electronic circuits which work and replace CMOS.

Therefore, CMOS is here to stay, even beyond nano-scale [5]. It will still have a lot of room left for further advancement beyond the nano-regime. This will not be easy, it will be faced with challenges [2], but they are not insurmountable.

6. Conclusion

We presented CMOS outlook in the nano-regime, history of electronics with three tenets that made electronics successful in the past, and using these tenets concluded that there is nothing on the horizon that has promise to replace CMOS at least in the next ten to fifteen years. Therefore, we will make CMOS work until then.

7. References

[1] Shekhar Borkar, "Design Challenges of Technology Scaling, IEEE Micro", July-August 1999.
[2] Shekhar Borkar et al, "Parameter Variations and Impact on Circuits and Microarchitecture", DAC 2003
[3] Shekhar Borkar, "Designing Reliable Systems from Unreliable Components: The Challenges of Transistor Variability and Degradation", IEEE Micro, November-December 2005.
[4] T. C. Chen, "Where Si-CMOS is going: Trendy Hype vs Real Technology", ISSCC 2006.
[5] George Sery, "Life Is CMOS: Why Chase the Life After?", DAC 2002.