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Circuit Components Based on New Materials: The Reality of Multitechnology System on Systems Hyperintegration

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The convergence of significantly different and disparate technologies such as spintronics, carbon nano tube field effect transistors, photon and bio-responsive molecular switches, memristor and memristive systems and metamaterials, coupled with energy scavenging sources are gaining a renewed focus in the quest for new products. This paper will provide an insight into an anticipated technological revolution and will highlight a futuristic Roadmap to capture opportunities that are brought about as the results of formulation of new circuit components basically driven by emergence of nanoscale materials as part of System on System integration. Challenges as the result of new lumped components such as memristor, metamaterial-based lumped components and the like that will challenge the designers' comfort zone will also be discussed.

Keywords: Metamaterial, Memristor, Optical signal processing, Volumetric thresholding, Metaphone

1. UNDERSTANDING OLD CIRCUITS WITHIN THE NEW DESIGN DOMAIN

The science fiction of yesterday depicted by such characters as Captain Kirk of space ship Enterprise and Dick Tracey has stretched the minds of researchers and technologists that no longer scaling of feature size predicted by Gordon Moore is seen to adequately provide the measure for future hypeintegration platform. While in the early 1960s Gordon Moore made his famous technology scaling predication, in 1959 the physicist Richard Feynman, foreshadowed that "there's plenty of room at the bottom," echoing the emergence of the new nanoscience domain. The want for ever higher density structures including that of the non-volatile memories, coupled with the need for a dramatic increase in on-chip data transfer rate is beginning to shape the future of lumped circuit elements as new composites

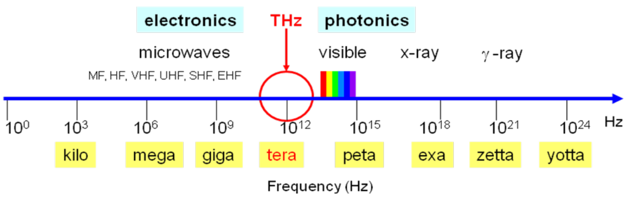

Fig. 1. Electromagnetic radiation spectrum illustrating regions of interest where the radio waves, THz, visible light, X-ray and gamma ray as part of the same electromagnetic spectrum that can be manipulated within the framework of Maxwell's equations that affect different mechanism for "current conduction" in various regions of spectrum.

with unique properties that are not found in nature are beginning to emerge. We are finally confirming Richard Feynman's vision that it is possible to "arrange the atoms the way we want" and more importantly to manipulate them in ways that on the

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surface appear contrary to our preconceived logical mind. In recent years as an example, the quest for an all optical signal processing, that could change the operating range from 10's of GHz to higher frequencies into terahertz (THz), infrared (IR) and visible wavelengths as shown in Fig. 1 has stretched the minds of researchers way beyond the way classical theories predicted material behavior has steered researchers into a new optical research domain [1-9]. In order to extend the operations of circuitry into the optical frequencies one needs to realize three important elements: 1) "optical circuit elements" such as optical resistors (R^o), capacitors (C^o), inductors (L^o), and now the 4th fundamental lumped circuits element, the memristors (M) [10,11] 2) proper optical channels for conduction of "optical currents" and 3) "optical isolators" to isolate different optical elements.

The trend will eventually lead us to integration of a multiplicity of independently engineered technologies rather than simply the silicon that has shaped the affairs of global community during the last half a century. This multiplicity of technologies will be the driving force to create unprecedented opportunities for realization of new 3D integrated systems sometimes defined as "fusion technology" or perhaps a more accurate description would be System on System (SoS) integration. The marriage of nanoelectronics and photon-based sciences with that of bio-driven engineering brings into the forefront the evolutionary progress of hypeintegration within SoS domain as the frontier for innovative products. For example projection of molecular processors as an alternative to complementary metal-oxide semiconductor (CMOS) technology in the recent International Technology Roadmap for Semiconductors (ITRS) report emphasises the significant challenges of device scaling [4,12].

In reality, Feynman foreshadowed the new roadmap for human-like machines in realizing models of the living computers, made from the DNA-like molecules that could be used to run calculations inside the human cells capable of priming the immune system at the first hint of illness or release drugs at targeted regions. Creation of new lumped circuit components small enough and driven by manipulation of Maxwell equations that results in other forms of current flow such as "optical currents, formalize a new frontier within the electromagnetic spectrum whereby through artificially engineered materials new architectures are realized. One measure of progress can be made by noting the volumetric nature of up-coming technologies where interaction of layered technologies match the application environment such as smart pills including the nanoendoscope, metasensors as part of computing cloud or for that matter the mobile phone and the like.

This paper is organized as follows: Section 2 provides an insight as to the inevitability of 3D hyper integration using volumetric thresholding as one parameter that maybe used to describe the Figure of Merit of a multilayered product using technologies that are either in their infancy or those yet to be uncovered through initiatives of material physicists, computational chemists, and bioengineers. Section 3 will introduce memristor, the 4th lumped electronic component followed by Section 4 where lumped optical components within the metamaterial domain are presented. Section 5 makes some observations in relation to the likely progress conjectured to challenge the current perspective and the mind-set that researchers and industry currently may have.

2. VOLUMETRIC THRESHOLDING

The evolution of SoS introduces an inherent 3rd dimension into future architectures that maybe described in terms of a

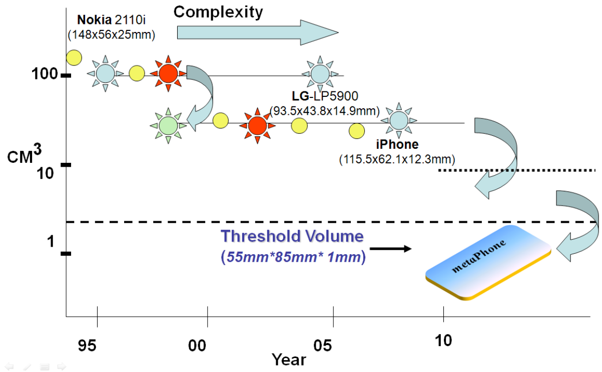

Fig. 2. Volumetric thresholding (V_MT) for mobile phone technology with technology evolution. With projected technology base and limitations imposed by physical interfacing and interaction V_MT is about 4.5×10^3 cubic mm for future smart phone or metaphones.

"Volumetric Thresholding Law" that takes into account the multitechnology nature of integration for a future whereby multitechnology becomes the new integration domain.

There are several physical layers of independent technologies that dictate the practical size and hence the geometric volume of a product. As the product matures both physical-limited and technology-limited factors defined in terms of volumetric thresholding (V_MT) dictate the eventual physical dimensions of the component that has to match a given environment. Improvements of each of the layers, which are invariably independent, will have consequences in terms of over-all performance. As an example, a century ago, Nathan Stubblefield, a Kentucky resident filed a patent for a wireless telephone. However it wasn't until the 1970s that personal mobile phone technology was taken seriously. Martin Cooper later-on made the first call on 3 April 1973, echoing the origin of the telephone that transpired a century earlier. As importance of the technology on the generality of human society became evident, the evolutionary changes driven by technology scaling created the foundation for a new way for human connectivity and social interaction as new options in functionality in the mobile phone were introduced. The concept of V_MT for the mobile phone is depicted in Fig. 2. Here the three components: the generator, the I/O interfaces and the processor determine the V_MT.

The I/O interface such as the dimensions of the screen in this example sets the limit on V_MT until a new man/machine bio-based interaction emerges. The concept of physical layers and the related simplified decomposition associated with the mobile hand-set is illustrated in Fig. 3. If practical length and width of the mobile phone is 85 mm × 55 mm, then within the framework of current known technologies, the cumulative thickness is likely to be about 1 mm which results in a volumetric threshold for the mobile to be about 4.5×10^3 cubic mm.

2.1 Dimensional "thinning" of the processor layer

With additions of new features into the mobile phone, and the anticipated emergence of metaphone, the computational complexity will place a heavy demand upon one of the layers such as the power source or the generator layer. One option towards reducing the power requirement would be to address the fundamental structure of the processor layer which is thus far being driven by Moore's law.

Traditionally there are only three fundamental passive circuit elements: resistors, capacitors, and inductors that are fundamental in circuits operation and determine circuit's performance

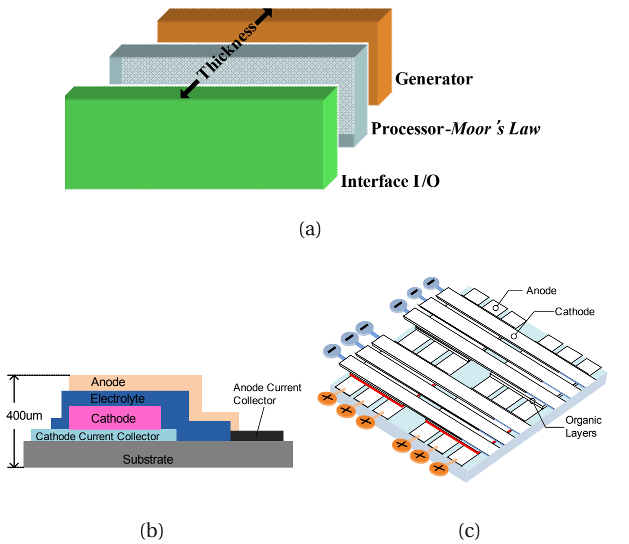

Fig. 3. Volumetric thresholding V_MT for mobile phone (a) physical layer decomposition (b) generator thickness: for example projected lithium battery thickness is about 400 μm (c) I/O interface: display thickness for example for passive-matrix of organic light-emitting diode is about 100 μm. The approach can be applied to numerous products.

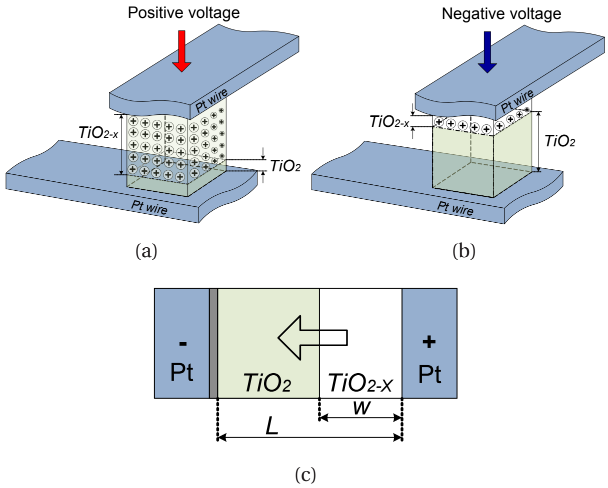

Fig. 4. Memristor switching behavior (a) R_{OFF}, "OFF" state corresponding to logical state "0" (b) R_{ON}, "ON" state corresponding to logical state "1" (c) dimensional relationship.

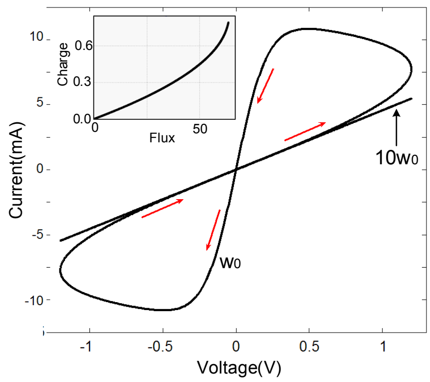

Fig. 5. Current-voltage behavior of memristor showing the nonlinear characteristic of the device. As frequency w_o is increased from w_o to 10 w_o the memristor behavior changes into a simple resistor. The behavior between flux and charge is also shown for convenience.

such as density, power consumption, delay and the like. One can set up five different mathematical relations between the four fundamental circuit variables: electric current i, voltage v, charge q, and magnetic flux ϕ. In 1971, Chua [10], proposed that there should be a 4th fundamental passive circuit element to set up a mathematical relationship between charge q and flux ϕ, ($F(q,\phi) = 0$), which he named the memristor M (a portmanteau of memory and resistor). Chua predicted that a class of memristors might be realizable in the form of a pure solid-state device without the need for an internal power source. At the time, no one really paid much attention as neither to the importance of this new component nor the significance of the discovery until the emergence of nanochemistry and related development of the research domain: the nanotechnology and related nanomaterials.

3. MEMRISTOR, 4TH MISSING FUNDAMENTAL LUMPED CIRCUIT COMPONENT

In 2008, Williams et al. [13,14], at Hewlett Packard, announced the first fabricated memristor device and presented a physical model whereby the memristor is characterized by an equivalent time-dependent resistor whose value at a time t is linearly proportional to the quantity of charge q that has passed through it. They illustrated the realization of memristor shown in Fig. 4 [14] which consists of a thin nano layer (2 nm) of TiO_2 and second Oxygen deficient nano layer of TiO_{2-x} (8 nm) sandwiched between two Pt nanowires (50 nm). Oxygen (O^{2-}) vacancies are +2 mobile carriers and are positively charged. A change in distribution of O^{2-} within the TiO_2 nano layer changes the resistance. By applying a positive voltage Fig. 4(a) to the top Platinum nanowire oxygen vacancies drift from the TiO_{2-x} layer to the TiO_2 undoped layer, thus changing the boundary between TiO_{2-x} and TiO_2 layers. As the consequence overall resistance of the layer is reduced which corresponds to an "ON" state. When enough charge passes through the memristor that ions can no longer move, the device enters hysteresis and it stops in integrating charge q but rather keeps q at an upper bound with M fixed. By reversing the process, Fig. 4(b), the oxygen defects diffuse back into the TiO_{2-x} nano layer. Resistance returns to its original state which corresponds to an "OFF" state. The significant aspect to be noted is only ionic charges, namely oxygen vacancies (O^{2-}) through the cell, change memristor resistance.

The resistance change is non-volatile; hence the cell acts as a storage element remembering past history of ionic charge flow through the cell. One of the best ways to define a memristor in terms of its voltage and current relationship is $v(t) = R(x)i(t)$, where x is the internal state of device [11].

This particular behavior is one of the most important properties of the memristor and simply illustrates that the charge that flows through the memristor dynamically changes the internal state of the element making it nonlinear. The second aspect of the characteristics to remember is that a memristor is a nonlinear element since its current-voltage behavior follows a 'bow-ties" or a Lissajous pattern shown in Fig. 5.

3.1 Simplified memristor model

Memristor can be modeled in terms two resistors in series, namely the doped region and undoped region each having vertical width of w and L-w as respectively as shown in Fig. 4 [14]. The voltage/current relationship defined as M(q), can be modeled as [15]:

$$v(t) = \left(R_{ON} \frac{w(t)}{L} + R_{OFF} \left(1 - \frac{w(t)}{L} \right) \right) i(t) \quad (1)$$

where R_{ON} is the resistance for completely doped memristor, while R_{OFF} is the resistance for the undopped region. The width of the doped region w(t) is given by:

$$w(t) = \mu_D \frac{R_{ON}}{L} q(t) \quad (2)$$

for R_{ON}<<R_{OFF} which is the case in digital circuits, Eq. (1) is modified to:

$$M(q) = R_{OFF} \left(\left(1 - \frac{\mu_D R_{ON}}{L} q(t) \right) \right) \quad (3)$$

where μD is the average dopant mobility ($m^2S^{-1}V^1$) and L is TiO_2/TiO_{2-x} film thicknesses. The highly none-liner characteristics of memristor, the inherent memory behavior, the nano-based feature and physical simplicity of the element creates an important framework for new architectures demanded by human-like computational engines and processors.

3.2 Neuromorphics and analog computations

Neural networks learn patterns that are based on an analog memory element, the synapse. Learning occurs when simultaneous voltage spikes are generated from detectors such as the edge detectors that characterize the human vision namely the eye. As the consequence the receiving synapse located in the brain responds to the stimuli by increasing its threshold value. Behavior of the memristor is similar where memristor changes its resistance state according to the stimuli - the voltage spikes - that it receives. In late 80's Carver Mead introduced the concept of neuromorphics within the context of very large scale integration (VLSI) that contained circuitry for which a network learns from repeated stimuli of connections between the nodes of the system emulating biological architectures. Neuromorphic domain takes inspiration from numerous fields including physics, mathematics, biology, and driven by new materials engineering to emulate artificial neural systems, such as autonomous machines, vision systems, auditory processors and the like [16]. The interesting feature of this design domain is the approach towards the formulation of architectures based on features that characterize biological nervous systems. It was already pointed out by Chua and Kang [11] that synapses have memristive properties, so if one wishes to build a neuromorphic processor having synaptic properties, then the fundamental 'gate' of such a system can be a memristor. The human brain has 10^{14} to 10^{15} synapses, but only about 10^{10} to 10^{11} as many neurons. Therefore the synaptic circuitry completely dominates and challenges the implementation of such architectures. Merolla et al. [16] has constructed synapses using 120 nm subthreshold CMOS technology, but the area of each synapse is rather large and similar to that of a neuron. This mean the neuron density is limited to only a few thousand per chip. A memristor however, is a small fraction of the size of any CMOS-only representation of a synapse namely (1/10,000). Furthermore, it is a non-volatile passive device, and requires very little power to operate. As the consequence it is a strong contender for future human-like processors with the capacity to emulate the basic biological primitives and hence bring into reality the realization of biologically inspired machines.

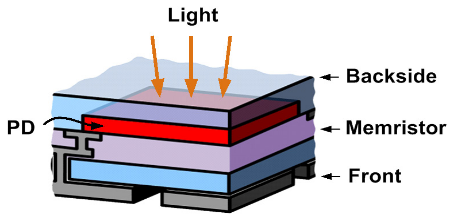

Fig. 6. Integration of optics with that of a memristor enables realization of circuit elements having the ability to convert light illumination from back-plane through photodiode (PD) into resistive state. Combination of CMOS and memristor array are on front of the integrated chip. Removal of power source still retains the history.

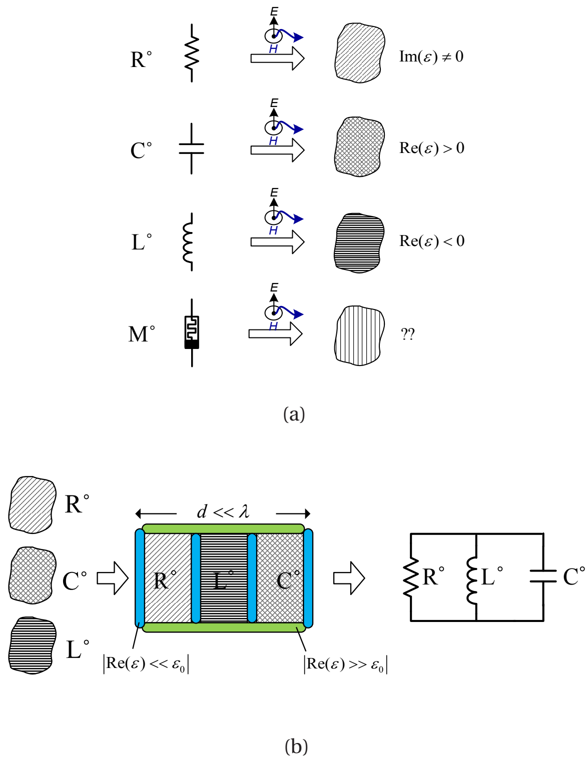

Fig. 7. Metamaterial based passive components (a) basic R°, L°, C°. Component representation together with a futuristic view of the inclusion of optical M (b) formulation of an integrated functional R°L°C° filter circuit after reference [9].

3.3 Ultra-high Integration density

It is predicted that in 2015 dynamic random access memory (DRAM) capacity will be around 19.55 Gbits/cm^2. However, memristors promise extremely high capacity around 100 Gbits/cm^2 to 250 Gbits/cm^2 [12]. In contrast to DRAM, memristor provides non-volatile operation similar to flash memories. Hence, the memristor could continue the legacy of Moore's law for many years to come as fundamentals of materials and the transport mechanisms are better understood. The implementation strategy as an example for an integrated back-illuminated CMOS image sensor using memristor as storage is depicted in Fig. 6

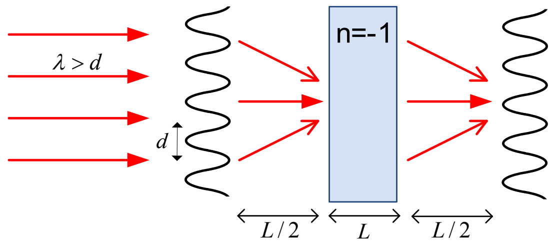

Fig. 8. Subwavelenght imaging where through implementation of negative index material(NIM) it is possible to overcome diffraction limits. Here $\mathcal{E}$= -1, μ = -1 results in n = -1.

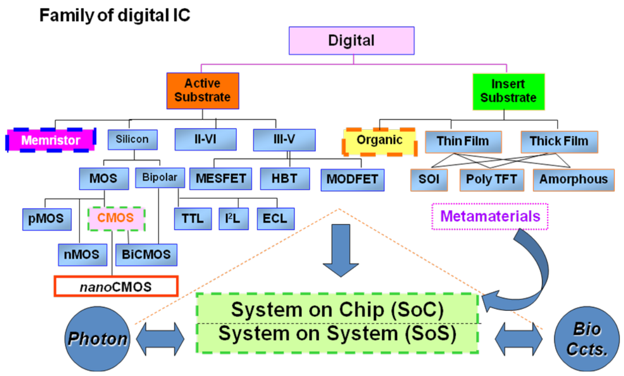

Fig. 9. Multitechnology roadmap towards System on System (SoS) Integration.

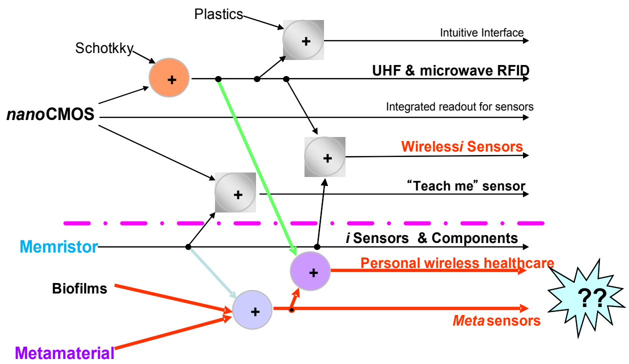

Fig. 10. Multitechnology interleaved integration.

demonstrating the concept of light to resistance state transformation.

4. METAMATERIAL CONCEPT OF LUMPED ELEMENTS

The physics of "small-scale" is the foundation for the understanding of metamaterial. It derives its name from the Greek word "beyond" or "after." Metamaterial is artificially engineered having unusual electromagnetic properties such as magnetic permeability μ, dielectric permittivity $\mathcal{E}$ and refractive index n that are not encountered in naturally occurring materials. The current trend of metamaterial research involves designing and fabricating nanostructures that are capable of manipulating electromagnetic waves at the visible frequency regime [17]. Metamaterials are artificial composites that acquire their electromagnetic properties from subwavelength metallic structures embedded within a substrate.

This means, they can add a degree of freedom that did not exist previously, in controlling the electromagnetic waves. It has recently been shown theoretically that by considering the displacement current as the "optical current," one can have optical capacitors, and inductors by using nanoscale dimension dielectric (e.g., SiO_2, Si_3N_4 or Si with Re($\mathcal{E}$) > 0 or metals (e.g. Ag or Au with Re($\mathcal{E}$) < 0), respectively, in which the optical loss of these elements represents their "resistivity." The generic concept is illustrated by Fig. 7(a). Figure 7(b) shows as to how these lumped components can be constructed to form a circuitry that operates at optical frequencies [9].

In an optical circuit it is required to have layers that act as "insulators" for the optical displacement current. The insulator layer should allow negligibly small displacement current in between the elements and stop the leakage. This is achievable by using materials where the real part of their relative permittivity $\mathcal{E}$ is very small: "epsilon-near-zero" (ENZ) materials. One of the approaches for creating ENZ materials is exploiting metamaterials. Metamaterials are engineered composite media, formed by stacking and embedding various sub-wavelength inclusions and inhomogeneities, which provides powerful tools in manipulating and tailoring electromagnetic waves. Their structure is composed of subwavelength metallic resonators assembled and held together within a dielectric. They acquire their electromagnetic properties from embedded subwavelength metallic structures. In theory, the effective electromagnetic properties of metamaterials at any frequency can be engineered to take on arbitrary values, including those that do not appear in nature. Therefore a new degree of freedom can be added to circuit concepts and design. The concept of metamaterials is not limited to the negative-index phenomenon. Indeed, other artificially engineered materials with unusual parameter values, such as ENZ (Re($\mathcal{E}$) << $\mathcal{E}_0$) are also considered as metamaterials. The salient feature of this new technology base is that it can be realized to have a wide range of electromagnetic characteristics at the wanted frequencies which are effectively not found in naturally occurring materials. Therefore by opening a new electromagnetic response space, metamaterials can offer new opportunities in the present optical design domain that most likely will result in a new frontier of research and applications.

The idea of optical circuitry in the THz domain for example, is appealing as in this frequency range, micro-size elements and channels that are compatible with present day fabrication process technology are required instead of the more complex nanometer size elements and channels in optical domain. In fact successful completion of these initial functional circuits in the THz domain by itself will be a significant improvement of signal processing speed compared to current state of the art nanoelectronic based circuits.

Beyond replacing traditional components, metamaterials offer a new range of devices that exhibit unusual effects following their extreme electromagnetic properties. As an example, superlenses shown in Fig. 8 which are able to amplify evanescent waves via exploitation of negative refractive index, have become a flagship application of metamaterials that attracts much interest in the radio, microwave, and optical regimes [6,18]. The latest efforts in metamaterial research will soon lead to optical nanostructures that are of primary importance to the fields of communication, and microscopy. By opening a new electromagnetic response regime, metamaterials offer immense opportunities in improving existing optical designs along with exploring unprecedented applications. Relevant research breakthroughs and visions proposed so far encompass: superlenses breaking the diffraction-limited image resolution, biosensors sensitive to small changes in the amount and response of a sample, magnetic wires retrofittable into existing magnetic resonance imaging machines for a better magnetic coupling, invisibility cloaks for hiding an object from detection, and illusion devices replacing the object image with a different virtual image [7, 8, 19-24].

5. INTEGRATED MULTITECHNOLOGY ROADMAP

Therefore integration of disparate technologies through further developments of new materials and formulation of those materials yet to be uncovered create unprecedented challenge for product creators. William Shockley formulated the basic structure for the bipolar transistors in 1948. However it took some 30 years before building actual integrated circuits could be realized. Progression of multi-technology leading us into SoS integration is illustrated in Fig. 9. An example of related outcome leading to new products is exemplified by Fig. 10. Circuit designers and architects need to become conversant with both the “bottom-up” design methodology that requires the understanding of underlying fundamentals but also the “top-down” architectural issues that most likely will be based on very different paradigms.

6. CONCLUSIONS

While the future is becoming more difficult to predict, most likely we could anticipate an accelerating pace of change that span across intelligent health care and health related sciences, environmental management, and smart energy manipulators through to innovations in new-IT and man-machine interaction and communications. For example, the ability of biomolecules to self-assemble into cells and yield dynamic complexes with highly ordered architectures on nanometer scale or alternatively nanochemistry agents to cause self-assembly/agglomeration of virus particles for precipitation and removal of “blood-waste” provide new opportunity for cell biologists to gain an entry point into nano-driven circuits that most likely will bring into realization construction of nano-engines. Albert Einstien echoed that “imagination is more important than knowledge”-highly pertinent at this juncture whereby the future of intelligent SoS technology based on revolutionary concepts are being mapped. This new frontier of research is conjectured to move us way beyond Gordon Moore's 2-D scaling relationship as we begin to uncover new relationships and principles. It is inevitable that new technologies such Memristor and memristive systems, and optical lumped components based on metamaterials will appear, become established, and produce their first impact that will be long remembered.

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