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Crude future vision of 300-GHz optical micro-processor units

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Abstract

Evolution in energy efficiency of many-core parallel micro-processors through year 2025 looks unclear nowadays, because the clock speed of new electronic cores has stopped to evolve. With reviewing on-going applications-research activities in semiconductor opto-electronics, instead, the author estimates what possibilities the potentially 100-times-faster serial-processing micro-processors (e.g. 300-Gb/s) consisting of all-optically-controlled gates and memories will contribute, to the information communication technology (ICT).

1. Introduction: New semiconductor industries

The semiconductor industry has recently been regarded as one of the most "competitive" industry, including cost competitions. It is mainly because of the 40-year-long maturity of crystalline-silicon nano-technology, and also because such silicon integrated circuits are utilized almost everywhere such as consumer-level wireless terminals and industry-level giant data centers. Now in this 21st century, in addition, it should be noted that several other types of semiconductor-material industries are newly attracting more attentions, too, as follows.

1. Wireless terminals: electronic semicond. (Si)
2. Network servers: electronic semicond. (Si)
3. Data centers: electronic semicond. (Si)
4. Optical-network systems: optical semicond. (non-Si)
5. LED room lights: optical semicond. (non-Si)
6. Flat displays: electronic semicond. with LED lights
7. Solar batteries: optical semicond. (Si & non-Si)
8. Smart-grid networks: electronic semicond. (non-Si)
9. Super-express railway: electronic semicond. (non-Si)
10. Electric Vehicles: electronic semicond. (non-Si)

This list reminds us that these semiconductor industries include many of those which are strongly

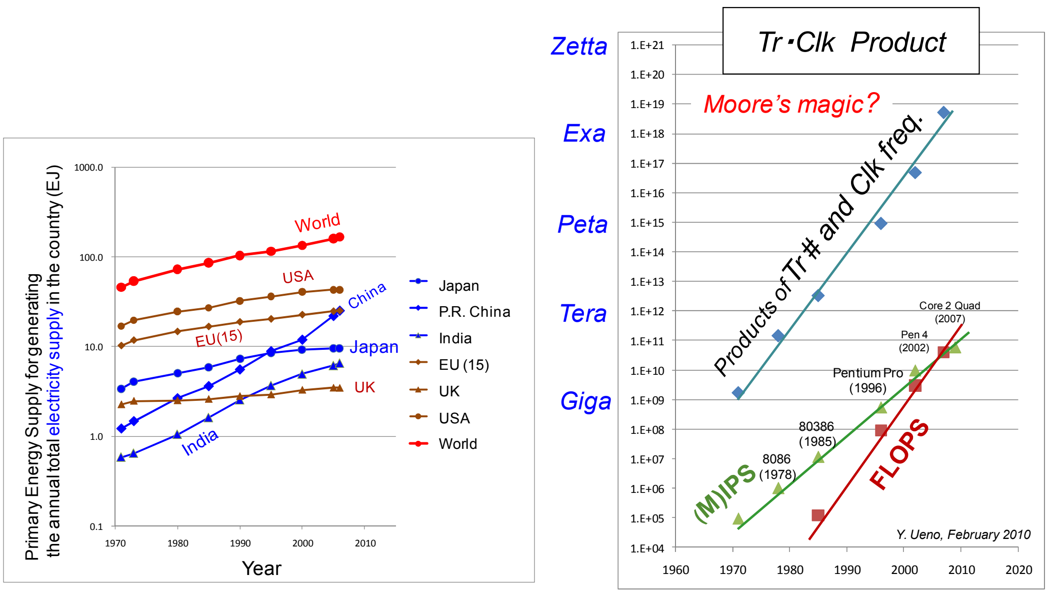

Fig. 1. 40-year-long increases in international-level energy supplies (a) and indexes of micro-processor performance (b).

expected to *save* our world-level energy consumptions in coming decades. It reminds us, too, the fact that we are already relying on several types of non-silicon-semiconductor industries, as well as silicon nano-technology. For example, the future electronic semiconductors in systems 8-10 will be non-silicon, that is, wider-bandgap nitride-semiconductors, since these high-power systems require robust semiconductor circuits that are tolerant to ultra-large electric currents at high temperatures. [Most of the active engineers, scientists, and students working in the above technical areas 1-10 are, by the way, steadily interacting with each other via international academic societies such as the Japan Society of Applied Physics (JSAP) and the Institute of Electrical and Electronics Engineers (IEEE) with "open" attitudes, since almost all of technical areas 1-10 have been covered by these broad-scope societies since long.]

Optical semiconductors in systems 4-7 are consisting of crystalline arsenide, phosphate, and nitride materials. After the 40-year-long history of research activities, opto-electronic properties and below-10-GHz responses of these optical semiconductors are already somewhat mature and described well in standard textbooks [1, 2]. Opto-electronic R&D activities for their above-100-GHz responses are, however, still very immature, and their experts exist in only limited number of research institutes in the world, partially because of the instrumental difficulties in such ultrahigh-speed characterizations.

In this talk, the author will review recent research progresses in ultrafast all-optical semiconductor gates and memories that have been studied and developed by several global research institutes, primarily for use in future optical-network node systems. The author will, then, introduce their recent trial series of estimations, i.e. what possibilities the potentially 100-times faster serial-processing micro-processors (e.g. 300-Gb/s, consisting of all-optical gates and memories) will contribute, to data-processing speeds in our information-communication technology (ICT), with paying attention to their electric energy consumption levels.

2. History of electronic micro-processors

In the last 40 years, our world has changed dramatically. Until 10 years ago, semiconductor devices, systems, and their heat dissipations used to be *not* consuming *nor* influencing any visible portion of the total primary energy supply (TPES, from crude oil, coal, natural gas, nuclear powers, wind powers, and few others) of ours, the mankind. Now in USA, data centers are consuming 1.5% of its nation-wide electric-energy supply [3], which corresponds to all outputs from 10 nuclear power reactors. In USA, the amount of primary energy supply (40 EJ/year= 40×10^{18} J/year) for generating the nation-wide electric energy occupies almost 40% of USA's TPES (100 EJ/year) [4].

Figure 1(a) shows the increases over the last 40 years, in primary energy supplies for generating electricity in selected countries including the above number (40 EJ/year from USA), according to the statistics in ref. [4]. The primary energy supply for generating world-wide electricity has reached 170 EJ/year. Silicon and other semiconductor materials are playing or about to play roles in almost all electricity-consuming systems such as computers, communication systems, back-lights of displays, and now room lights. Many of the biggest impacts to our world in the last 40 were, and those in coming 40 years will be strongly influenced by semiconductor materials industry and particularly by the performance of micro-processors.

Instead of the number of transistors which appears to follow the Gordon Moore's law [5], Fig. 1(b) in this work shows the product of clock frequency and transistor number (Tr·Clk), measured floating-point operations per second (FLOPS), and measured instructions per second ((M)IPS) of micro-processors in the last 40

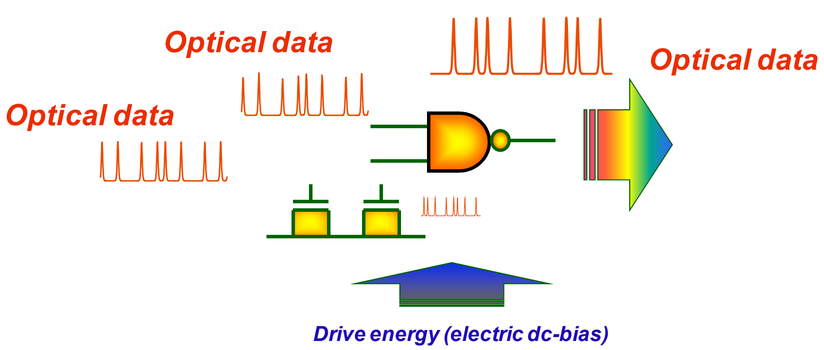

Fig. 2. Fundamental elements of optical processors consist of optical logic gates and optical buffer memories [7-18].

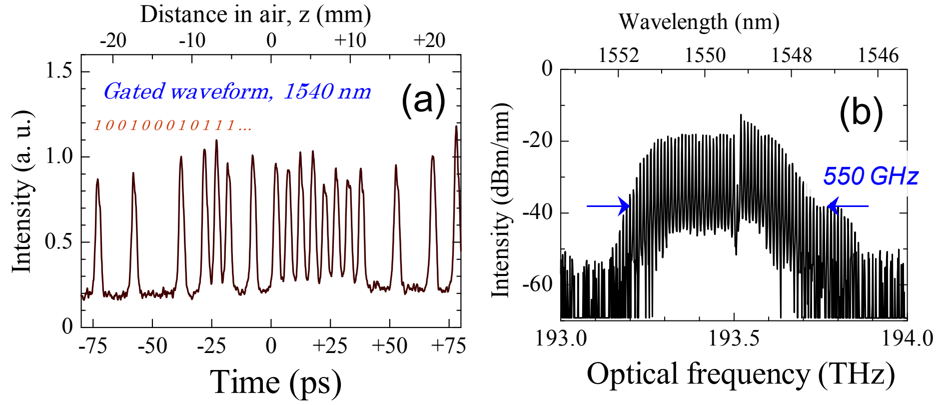

Fig. 3. 200-Gb/s data waveform generated by our III-V semiconductor optical gate (a)[15], and the 550-GHz bandwidth of optical clock generated with a similar optical-gate scheme [12]. The ratio $\Delta f/f_0$ of this bandwidth (550 GHz) to its center frequency (194 THz) is only 0.3%.

years since its birth in 1971. This figure suggests that the big growth of the order of 10^{10} in FLOPS is proportional *not* to transistor number Tr *but* to the product Tr·Clk. It suggests next that the factor of 10^4 (among the factor 10^{10}) came from growth in Clk, while the other, much larger factor of 10^6 came from the Moore's law (growth in transistor number Tr).

The larger growth factor (10^6) from Tr than that (10^4) from Clk is quite symbolic; nearly 40 years we had already relied on, and will rely with coming many-core processors on the even furthermore-folded parallel-processing architectures which consist of command-level, intra-core-level, intra-processorlevel, intra-sever level, and intra-network level, rather than the transistor speed. Many network applications will tolerate with more-folded parallel architectures, such as video streaming, in which time delays between packet arrivals and machine loads in packet-reconstruction procedures are accepted somehow. Other applications may not tolerate, however [6]. For such *parallel-processing-intolerant* applications, it would be very difficult for skilled programmers to keep the time-to-output efficiency in their tasks, and/or to enhance the system performance per unit energy in the coming 40 years.

In the above majority R&D direction with developing more and more cores, the time-domain speed of transistors seem to completely stop to grow beyond 3 GHz. Instead of speed, the coming big challenges are located in the new few generations of ultra-fine lithography, and newly in the increasing microwave losses along the intra-processor microwave-guided connections, rather than new challenges in transistors themselves. The microwave-connection-loss issue is inherent and will be enhanced more by the still expanding parallel-processing architectures. [The modern MPU's internal-connection-loss issue is inherently large, because the bodies of all "electronic data signals" inside high-speed MPU's are not at all electron currents but electro-magnetic waves which are inherently absorbed by metallic wires themselves and also easily dissipated (radiated) to outside strongly-bending metal/dielectric/silicon waveguides.]

An ultimately alternative direction has been widely recognized so forth, to be the extremely-quantum signal-processing system (called as quantum computer) since nearly 20 years ago. It has been believed, however, to take care of a very limited range of data-processing types only, such as prime factorizations for breaking RSA-encrypted security data in extremely shorter times.

3. 300-GHz optical gates and memories for future network systems

It seems safer for us in coming 40 years to have an option other than the above two R&D directions (that is, furthermore-parallel-processing architectures with fixed speed or new quantum computer). We do have one option, in fact; Near the middle point of the above two alternative directions, a group of international research institutes have been studying in the third direction, that is, optical signal-processing devices and materials [7-18].

In Fig. 2, the elementary functions that this group of institutes has always been keeping in their minds are symbolically drawn. More specifically, this group of institutes has been trying to develop optical de-

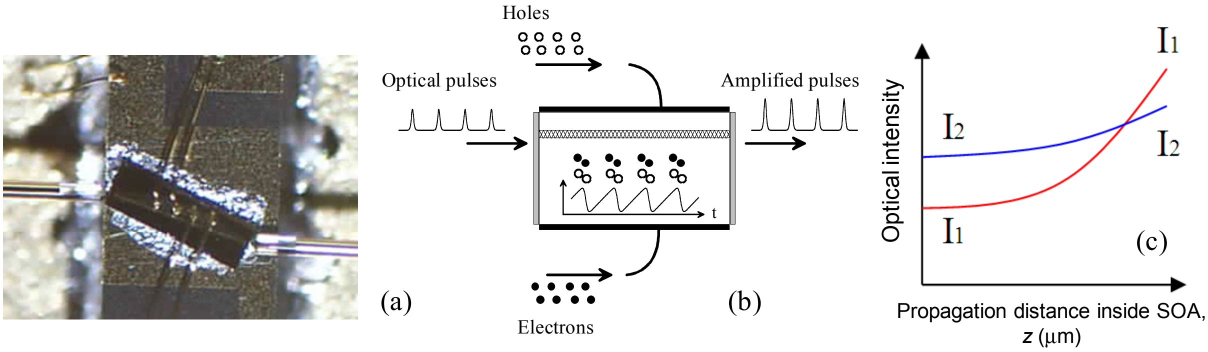

Fig. 4. Top view (a) and physics (b) of semiconductor optical waveguide-amp material, being coupled with input and output optical fibers. The typical width and depth of amp-waveguide structures are only 1×3 μm², while the length of this amp was 1,100 μm.
One of the most interesting subjects is to improve the energy efficiency in the processes of optically accelerating the gates [20], taking into account the undesirable amp-gain competition between the two separate-wavelength input components, which had been decreasing the energy efficiency in conventional schemes (c).

multiplexers, optical wavelength converters, optical 3R-repeaters, synchronized optical clock sources, optical buffer memories, etc. so that these devices and sub-systems work in the near-future optical communication systems. Some of recent research results from our institute (UEC, Tokyo) are shown in Fig. 3. The typical optical data speed has reached nearly 200-to-300 Gb/s [11-13, 15]. The typical electric-dc-bias energy consumption has been improved dramatically to less than 10 pJ/bit [14], from much larger energies 10-to-20 years ago. The sizes of elementary gates and buffers are, in contrast, apparently much behind (larger than) modern electronic processors; The typical sizes are presently of the order of 500×500 μm^2 (before incorporating several types of nano-photonic wave-guiding techniques in which Si-compatible electron-beam-lithography techniques are applied [19]).

4. 300-GHz optical gates and memories for optical micro-processors in future

Almost all of previous research goals had been limited to those within optical-communication-node systems, and therefore the goals had not yet been expanded to an optical-processor vision, mostly because of their spatial sizes and partially because of their electric-bias-energy levels which might still look behind electronic processors. Nontheless, being triggered by the above-mentioned status of electronic micro-processors, we have started estimating the potential performance of optical processors, with taking into account potential progresses in their energy consumption and size, from material physics viewpoints (i.e., semi-classically-quantum opto-electronics with III-V semiconductor materials). Thus estimated potential performance is consisting of general pros and cons of optical processors. Depending upon these pros and cons, the group of parallel-intolerant signal-processing applications will be specified better, hopefully in collaboration with computer specialists. This type of activities will support the long-term R&D of all-optical logic-gate devices for use in ultrafast network-node systems, as well.

5. More-recent research activities of optical gates

The amount of dc-electric power consumption P_{gate} of a typical, 200-Gb/s-level optical gate is of the order of P_{gate} = 300 mA × 2.0 V = 600 mW, 70% of which is occupied by the Joule heat energy discipation from its internal Ohmic resistor components (which are always located outside the optically active semiconductor region of the gate). The dc power consumption for generating input optical signals will not dominate in the total consumption. As a consequence, the energy consumption per one gate unit per one data-bit is derived to be 3 pJ/bit. The number of continuously injected quantum electrons is calculated from the amount of dc current to be of the order of 1×10^7. The amount of electron consumption and consequently the energy consumption are generally influenced first by the gate scheme and second by the scheme of optical acceleration [8, 11, 14]. Previous

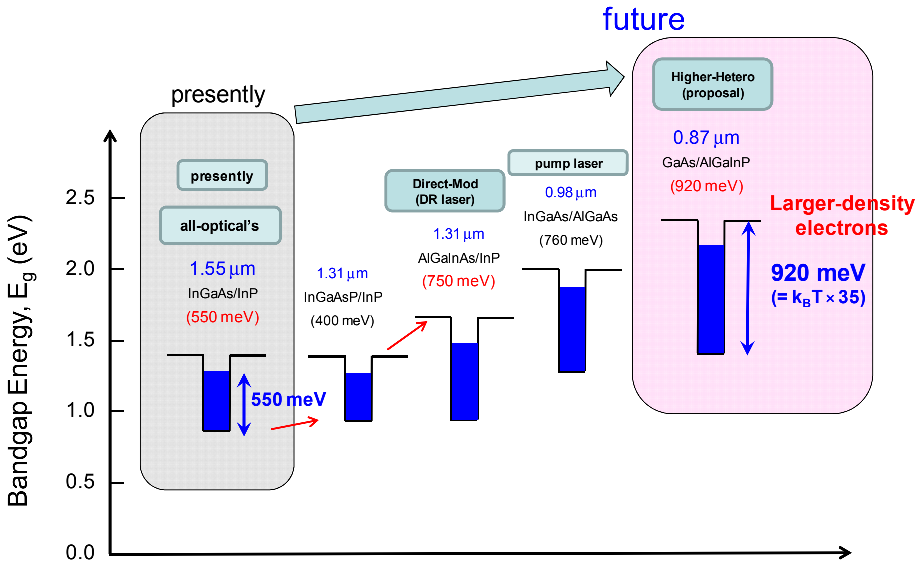

Fig. 5. Long-term proposal of a new lattice-matched hetero-structure system GaAs/AlGaInP that will activate exponentially-larger-density excited electrons in all-optical gates (with 0.87-µm optical data), and consequently improve both energy efficiency and spatial size of optical gate units, since this system expands the hetero-barrier energy ($\Delta Eg = \Delta Ec + \Delta Ev$) from conventionally 550 meV up to 920 meV ($=k_B T\times 35$).

research activities from this viewpoint had, however, been relatively poor in related research institutes in the world. One of the purposes of our recent research [14, 16, 20, 21] is to make the above-mentioned electric-energy-consumption levels clearer and then more efficient, step by step.

The new original viewpoints, to our knowledge, from which we are or we will be experimentally studying are, for example:

1. Linear-optical-spectrum-synthesis gate scheme which removes inherent output waveform distortions more effectively [16].
2. Degenerate-wavelength, polarization-discriminating scheme which will accelerate the gate more effectively [20], than conventional two-wavelength input schemes [11-13, 15] (Fig. 4).
3. To move from conventional active-layer structures (bulk and MQW's) of semiconductor optical amps, to one or two new groups of photonic structures for designing more energy-saving refractive-index modulations.
4. To characterize the dependences of the amounts of both refractive-index- and gain-modulations on the optical-data's wavelength (i.e., optical frequency) [21], when those optical data are input to a group of semiconductor structures at applicable ranges of electron-excitation levels, particularly for supporting the above viewpoints 2 and 3.
5. To move from the conventional InGaAs-core, InGaAsP-clad system (with 1.55-µm-wavelength optical data), to the new GaAs-core, AlGaInP-clad still-lattice-matched system (with photonic-inter-connection-compatible 0.87-µm-wavelength data), for improving both energy efficiency and gate size, furthermore (Fig. 5).

In this talk, with introducing the [speed, energy, and size] dimensions of all-optical gates and memories under research, we will present an outline of the above-mentioned computational performance estimations towards mankind-first "300-GHz optical micro-processor units." Any sudden ideas, weird ideas, or fundamental questions are always welcome during and after the talk.

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