MERGING ELECTRONICS AND MICRO & NANO PHOTONICS IN INTEGRATED SYSTEMS

MEMPHIS: a smart

The Memphis project, funded by the Dutch Smart Mix innovation programme, focuses on developing an integration platform for high-frequency electronics with micro- and nano-photonics. The consortium with 23 partners from SMEs, multinationals, universities and institutes brings together the best players in the Netherlands. The limitations of present electronics require a new massive converging technology based on complementary characteristics of "micro- and nano-electronics" and "micro- and nano-photonics", utilizing the best of both technology worlds. A low-cost combination of the processing power of classical CMOS IC technology, the high-frequency capabilities of modern high-frequency (HF) electronics, and the large bandwidths offered by integrated photonics creates the technology for novel broadband miniaturized electronic-photonic devices. This article focuses on the Production Processes and Equipment subprogramme of the Memphis project.

• *Lis Nanver, Ruud Polmans, Arne Leinse, Lorraine Flannery and Hans Mulders* •

Memphis
Merging Electronics
and Micro & Nano-Photonics
in Integrated Systems

The partners in Memphis investigate new complex miniaturized devices with vastly increasing functionalities against the lowest possible cost price, which cannot be fulfilled with present micro-electronic technology alone. In order to balance the "market-driven" and the "technology-pushed" technology developments within the Memphis project, several subprogrammes have been defined, focusing on Applications, Technology, Devices and Systems, and Production Processes and Equipment. This article is mainly concerned with Production Processes and Equipment, thereby highlighting the impressive

mix of electronics and photonics

contributions of Dutch companies in building machines and production equipment for high-tech systems as well as paying specific attention to concrete results in the Memphis project.

Introduction

Most authoritative scenarios for the development of technology show optimistic views on how our life will be changed by an ambient, intelligent, comfortable and safe environment, by continuous health monitoring, by personal communication and by early detection of threats from nature, technical failures and human activities. These areas of interest require the aforementioned new complex miniaturized devices. The limitations of present electronics require a new massive converging technology based on complementary characteristics of “micro- and nano-electronics” and “micro- and nano-photonics”, utilizing the best of both technology worlds. A low-cost combination of the processing power of classical CMOS IC technology, the capabilities of modern high-frequency (HF) electronics and the large bandwidth offered by integrated photonics creates the technology for novel broadband miniaturized electronic-photonic devices. This will open the way to major new applications for the use of light: in medical diagnostics, for healthcare, entertainment, telecommunications, tracking and positioning; see Figure 1. Underlying technologies are ultra-fast signal processing, terahertz imaging, broadband communication technologies, sensor technology, Raman spectroscopy, laser imaging and light sources.

Authors

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www.tudelft.nl
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Consortium

In 2006, Dutch government stimulated the convergence between and the development of nano- and

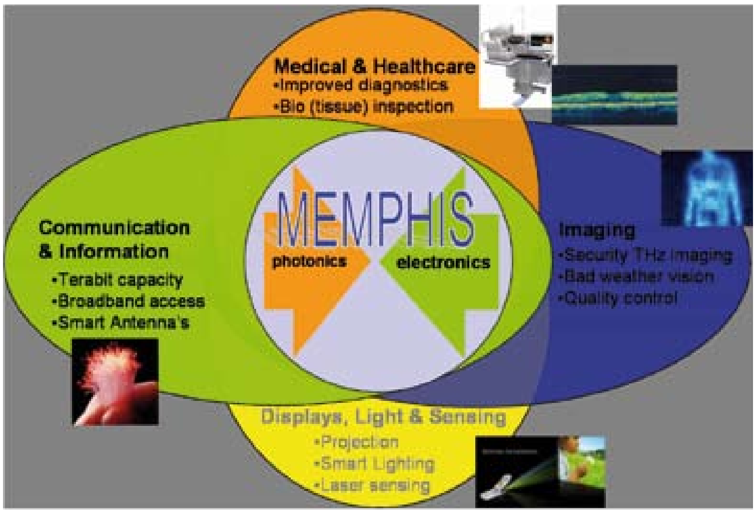

Figure 1. Memphis application areas.

microelectronics and -photonics by disposing subsidy from the Smart Mix innovation programme to the Memphis project. The MEMPHIS project, being an acronym of Merging Electronics and Micro & nano PHotonics in Integrated Systems, is constituted by an excellent consortium consisting of five multinationals, like Philips, ASML and Alcatel, six SMEs, including LioniX, Genexis and Tempress, six university-related research groups, amongst others from the Erasmus Medical Centre and the three Dutch universities of technology, and five research institutes, like AMOLF, TNO and IMEC. This eminent and complementary character of the consortium corresponds to the ambition and the challenge of the project.

The ambition of the Memphis project is to create and exploit synergy effects between the disciplines of electronics and photonics or, in other words, to combine the best of both worlds. This challenge can best be appreciated against the historical background of the main technological force boosting the market for electronics, Moore's law. In the mid-1960s, Gordon Moore, one of the founders of Intel, argued that the capacity per area of electronic integrated circuits (ICs) was doubling every 18 months. However, this miniaturization principle of Moore's law will not be perpetuous, so the concept of "Beyond Moore" has been introduced.

Beyond Moore

Apart from miniaturization, enhancement of functionality of micro-devices can also be achieved by diversification, i.e. the introduction of new technologies which will generate even more opportunities than Moore's law. Extending the opportunities of basic micro-electronic designs by other physical phenomena and other materials will therefore be of great interest in the years ahead. The most promising option is the merger of micro- and nano-electronics with micro- and nano-photonics. Whereas the classical CMOS IC technology (logic) offers a huge data processing power and modern high-frequency electronics has outstanding wireless connection capabilities, micro-optics is a very versatile technology offering complementary properties. The usage of micro-optical technology is best known in ultra-broadband (data) communication. Also extremely fast signal processing is strongly related to photonics. Additionally, interaction of light and matter offers unique options, for example for materials characterization and processing, for data stream handling by photon manipulation, future illumination and display techniques.

The option of merging the complementary technologies of micro- and nano-electronics and micro- and nano-photonics, being extremely promising for the achievement of outstanding properties for a large amount of applications suited for many markets, therefore constitutes the heart of the Memphis project.

Production machines

Within the Memphis project, the role of the Applications subprogramme is to create a structure in which the technological research and development activities are continuously linked to the market demands for future applications. The Technology research and development subprogramme is the foundation of the project enabling the various levels of integration of electronic and optical circuits and functions. Because a project as substantial and profound as Memphis, has to cover the total supply chain, the subprogramme Devices and Systems addresses new physical phenomena in advanced structures which will be the basis for new electronic-photonic building blocks. Finally, to create and produce novel electronic-photonic devices and systems, new production processes and associated new production equipment must become available – this is covered by the Production Processes and Equipment subprogramme.

With respect to this final subprogramme, it is interesting to note that Dutch companies have significantly contributed to an impressive history of building machines and production equipment for high tech systems. Apart from the participation of ASML, as the world-leading manufacturer of lithography systems for the semiconductor industry, the activities of companies like Tempress, Lionix, FEI and Alcatel as well as universities like Delft University of Technology have in particular been focused on the world of electronics. It is one of the main challenges in the Memphis project to extend this expertise and experience to the development of production equipment for photonic devices as well. The remainder of this article will highlight some of the progress made in the Memphis project regarding this development of production equipment for photonic devices. The focus will be on impressive results from, respectively, Alcatel, Delft University of Technology Delft, Tempress, ASML and FEI. As a result, it will become clear that the Memphis project contributes greatly to merging the worlds of micro- and nano-electronics and micro- and nano-photonics.

Etch depth control in Inductive Coupled Plasma etching – Alcatel

In the fabrication of micromechanical structures, Inductive Coupled Plasma (ICP) etching is a good technology to etch anisotropically in different types of material. In these etchers the plasma is induced by electrical currents which are produced by electromagnetic induction, that is induced by time-varying magnetic fields. These etchers can be used for different types of materials, like Silicon (Si), Silicon On Insulator (SOI) as well as for III-V materials like InP and GaAs; see Figure 2. Within the Memphis project, Alcatel supplied an ICP etcher offering superior process performance including very high etch rates, high mask selectivity, excellent etch uniformity and profile controls. However, these ICP etchers until very recently have most often been used for "deep" etching in Si, SOI or glass wafers, i.e. for the world of micro- and nano-electronics. Using the ICP equipment, however, for e.g. so-called TriPLeX™, i.e. for photonic applications, very different demands are set regarding the equipment. In optical waveguides the etch depth is very often small (~ microns) while the demands for footprint control and sidewall roughness are very strict.

Within the Memphis project, an ICP etcher has been developed which is particularly valuable for the realization of TriPLeX™ waveguide structures. Whereas in some applications the challenge for the etcher is to etch in a material as deep as possible, in the realization of TriPLeX™ the exact process control is much more important. Since the exact etch depth determines the performance of the waveguide, etch depth control better than 50 nm is needed.

In order to develop equipment for proper usage in optical waveguide etching, Alcatel has varied several parameters to find the specific relations between the etched structures and these parameters. For example, experiments have been done by varying (bias) power, gas flow, temperature, pressure, sample distance and mask material. Results of these experiments now lead the further development of specific ICP-etchers for optical devices.

Epitaxy of III-V compounds and Si/SiGe – Delft University of Technology, DIMES

The success of merging photonics with electronics will to a great extend depend on the degree to which the materials used in the two realms can be merged. Basically, this means merging III-V semiconductors such as GaAs, GaN and InP with silicon, being the "workhorse" of the CMOS industry. In the Memphis project, the accessibility of this merger is brought closer by the development of a new tool for III-V Chemical Vapor Deposition (CVD).

Conventionally, CVD of these materials is achieved from high concentrations of gases, including metal-organics, in equipment referred to as MOCVD epitaxy systems. The high gas concentrations, particularly of the highly toxic gases arsine (AsH_3) and phosphine (PH_3), mean that severe safety precautions must be implemented when running MOCVD. For this reason, most MOCVD III-V material fabricated today is produced in dedicated laboratories not directly connected to Si cleanroom facilities.

In the Memphis project, for the first time the growth of both III-V compounds and Si/SiGe has been demonstrated in one and the same CVD system. A commercial CVD system (of ASMI, see Figure 3) has

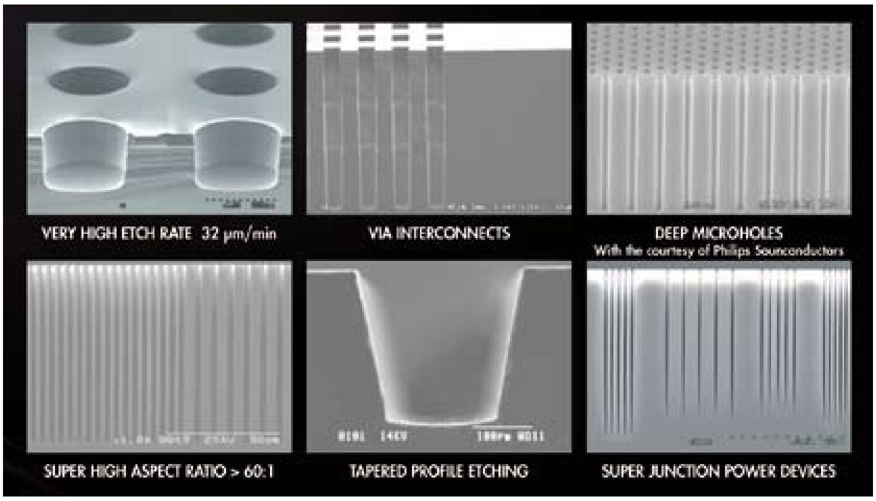

Figure 2. Silicon etching process examples obtained on Alcatel's Inductive Coupled Plasma etcher.

Figure 3. The ASMI Epsilon 2000 CVD system and its reactor chamber (inset). In Delft, this Si/SiGe epitaxy system has been specially equipped for the growth of III-V compounds in a manner that does not exclude use for Si-based depositions.

been developed for the growth of III-V compounds in a manner that does not exclude the use of the system also for Si-based depositions. For this purpose, the Si system was extended with a TriMethylGallium (TMGa) bubbler and extra tubing to allow the deposition of III-V semiconductors such as GaAs and GaN in addition to the standard Si and SiGe depositions. A very low arsine concentration is applied: 0,7% as compared to the values normally used in MOCVD, which are at least ten times higher. The correspondingly low concentration of TMGa means that contamination of the reaction chamber with Ga or As is so low that standard high-quality low-doped Si and SiGe depositions can still be performed in the same chamber. Moreover, the low gas concentrations permit the system to be run with the same safety precautions that apply to a normal Si/SiGe reactor. Thus there is no issue with respect to adding this equipment to a CMOS cleanroom environment. Finally, it should be noted that, in spite of the very low AsH_3 concentration resulting in a correspondingly low growth rate, GaAs growth rates of 1 to 5 nanometer per minute have been achieved. Such values are acceptable for many of today's device applications for which layers in the 100-nm range are required.

Optimizing atmospheric and LPCVD equipment – Tempress

In order to be able to produce high-quality, low-price and high-volume products with integrated optical and electronic devices, existing production equipment has to be optimized. Within the Memphis project, Tempress researches and develops atmospheric and LPCVD (Low-Pressure CVD) equipment for the fabrication of the optical waveguides based on the TriPLeX^{TM} structures.

The new equipment enables achieving optimal material characteristics. For example, fine tuning is possible with respect to layer thickness, refractive indices, uniformities, reflow characteristics and compatibility with other processes. Another specific challenge for Tempress is to design and build a new horizontal LPCVD furnace that has much tighter specifications than a normal LPCVD furnace. In order to achieve these results a new furnace frame has been developed. This frame contains a new loading system for the ATM (atmospheric) oxidation furnace that makes faster loading possible. Also, cleaner process results can be achieved because no unwanted materials stay in the process tube. Moreover, to get cleaner LPCVD furnaces a new way of vacuum line heating has been designed: individually controlled heated sections ensure that particle formation is minimized. These kinds of optimization of the existing atmospheric and LPCVD equipment enable the definition of an improved CMOS-compatible optical backbone circuit.

The specific requirements of complex photonic devices – ASML

The photonics market has a unique set of challenges that need to be addressed on equipment that was originally driven by the manufacturing needs of the Si-oriented semiconductor industry on 8- and 12-inch substrates. The photonics market consists of a plethora of devices, manufactured from a variety of material systems and using a wide range of technologies, each with their own set of application-specific requirements. This translates into system adaptations needed to take into account the physical properties of the material systems (e.g. substrate type, size, fragility) and the consideration of the application requirements of a large number and variety of components to find the best overall lithography solution.

Imaging solutions down to a (half pitch) resolution of ≤ 150 nm for 3- to 8-inch substrates and to ≤ 90 nm for 8-inch substrates are available on the PAS 5500 platform; see Figure 5. ASML is collaborating with the COBRA

Figure 4. Tempress equipment developed within the Memphis project: the LPCVD and atmospheric oxidation furnace. From left to right: touchscreens for process control; loader units (the upper one for the newly developed ATM process, the lower three for LPCVD); and four gas systems, one for each process (behind them, not visible, the process chambers).

Institute at Eindhoven University of Technology to facilitate the development of a special carrier to allow Deep UV lithography solutions down to ≤ 100 nm on 2-inch substrates and wafer pieces for R&D purposes in InP Photonic Integration Technology. In order to reduce prototyping cycles for photonic and electronic integrated circuits, ASML has developed Compound Image Design (CID) software which enables the easy creation of compound images as large as the wafer itself, giving maximum flexibility for multi-product wafers. It also allows stitched designs that are larger than the lithography systems imaging field or contain more than one occurrence of a pattern.

In addition to the different material systems and device design considerations, the lay-out of planar photonic components does not adhere to the same design rules as used in Si-based micro-electronics, where similar structures are imaged on the same layer and the size of the feature never exceeds the half pitch. Most of the patterns used in photonics are non-orthogonal (curved geometries) and require precise critical dimension (CD) control. In addition, to meet strict alignment criteria, photonic components which are incompatible from an imaging perspective are printed on the same layer. All ASML PAS 5500 systems can be configured with a number of different imaging, overlay, productivity and focus improvement options depending on the application requirement to extend manufacturing for challenging layers.

Deposition of gold by Electron Beam Induced Deposition – FEI Company

For photonic and plasmonic structures a thin film of gold is one of the most relevant base structures. Local functionality can then be achieved by creating a micro- and nano-scale structure within this film. The main reasons for this interest in gold are its optical behavior as well as its good conductivity. Unfortunately, that same element of gold is a forbidden material in any CMOS factory due to its high mobility in the semi-conducting base material and its capability to reduce the junction performance, and hence kill the device locally. As a consequence, gold patterning has not been of major relevance in the CMOS industry. When merging micro- and nano-electronics with micro- and nano-photonics, the issue of creating and modifying small structures of gold becomes however very relevant.

Figure 5. The PAS 5500/1150 193-nm Step-and-Scan system enables cost-effective 90-nm ArF mass production.

Figure 6. The Magellan is FEI Company's latest commercial instrument in the high-end range of SEM. It can be used for imaging the latest challenges in electro-optic structures, and its development was supported by the Memphis project.

Standard patterning of gold is done by optical and electron beam lithography, using resist patterning and lift-off generation of a suitable mask. However, in the early development phase of creating and modifying plasmonic structures, these methods are not very flexible, require a multi-step approach and only offer a 2D patterning capability. Moreover, lift-off using electron beam lithography also easily suffers from inhomogeneities in structures, when looking at the nanoscale.

Another solution for direct deposition of gold is by Electron Beam Induced Deposition (EBID). This technique is relatively new and recent developments focus on direct deposition of conducting (platinum, tungsten) or non-conducting (SiO_2) materials. The basis of this technique is the in-situ gaseous delivery in a SEM (Scanning Electron Microscope; see Figure 6) of a precursor gas that adsorbs on the surface. When the electron beam hits the surface, locally induced electrons decompose the adsorbed layer, creating both volatile and non-volatile parts. The latter is the metal of interest, while the former parts such as CO are pumped off by the vacuum system.

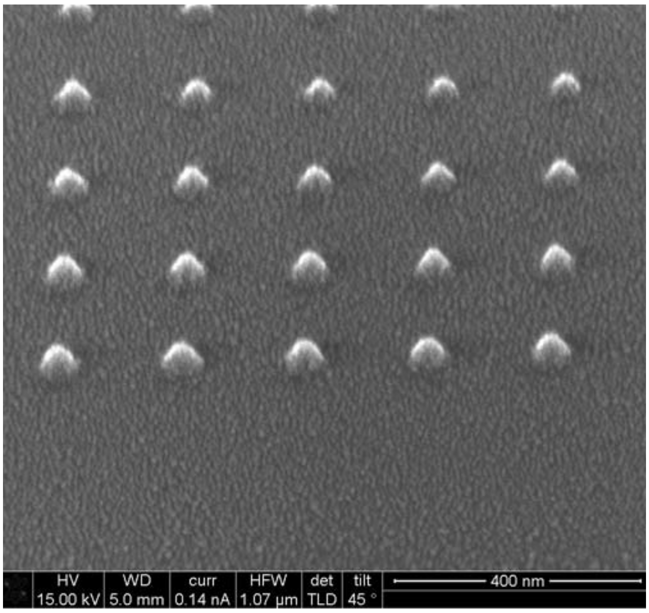

Figure 7. An array of nano-scale gold dots created by direct electron beam induced deposition. The structures are around 35 nm wide and 30 nm high. The purity of the gold is > 95 at% and the creation time of the 10x10 matrix is around 3 minutes.

This direct deposition technique is very promising, but for the deposition of gold the purity of the material is too low. For this reason a new process has been developed within the Memphis program that allows the deposition of nanoscale 100% pure Au by direct-write EBID; see Figure 7. This process can now be used for the creation of complete structures, but also has the capability to locally add gold to a non-homogeneous Au structure created with e-beam lithography. In this way, it is possible to repair non-perfect structures.

Conclusion

The new processes and equipment developed within the Memphis project will become instrumental for the merging of micro- en nano-electronic functionalities and the micro- and nano-photonic devices that will make up the next generation of products. These new products can be made at lower cost and with increased functionality in a smaller footprint. The Dutch companies that participate in this Memphis project have made a substantial contribution to the new requirements of merged electronic and photonic devices.

Information

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