GaAs Optoelectronic Integrated Circuits for Gigabit Ethernet

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Abstract - The ability to integrate MSM photodiodes on the same chips with transimpedance preamplifiers differentiates Gallium Arsenide (GaAs) from Silicon for Gigabit Ethernet applications. It also signals one of the first practical applications of optoelectronic integrated circuits (OEICs). In this talk, we'll review the explosive Gigabit Ethernet market and the various GaAs IC's and OEICs that are poised to serve the market.

I. Introduction

While silicon has been the material of the electronics industry, GaAs has long been the semiconductor for optical devices due to the direct bandgap properties. Recently, GaAs-based technology has begun to find mainstream applications in the data communications market. The use of GaAs optoelectronic integrated circuits (OEICs) has increased the performance of high speed components for Gigabit Ethernet systems. In addition to smaller size and better performance, an added benefit of GaAs OEICs is the reduced costs compared to discrete diode and transistor solutions.

II. GaAs OEIC Devices

GaAs-based devices utilized in OEIC manufacturing are listed in TABLE I. The table shows common electronic and optical devices grouped by device type. GaAs devices are produced using either ion implantation or epitaxial material growth. Epitaxial growth on GaAs substrates, primarily Molecular Beam Epitaxy (MBE) and Organo-metallic Chemical Vapor Deposition (OMCVD), is necessary to produce these devices which contain heterostructure materials such as AlGaAs and InGaAs. Heterostructure materials provide the flexibility to tailor the properties of the devices at the expense of material cost. Both the MESFET and the metal-semiconductor-metal (MSM) photodiode have been manufactured using non-epitaxial processes, which helps to reduce the cost.

TABLE I: GIGABIT ETHERNET OEIC DEVICES

Electronic Devices	Optical Devices
• Field-Effect Transistors MESFET PHEMT	• Photodiodes MSM PIN
• Bipolar Transistors HBT	• Sources LED VCSEL DFB Laser

The electronic devices listed are well suited for Gigabit Ethernet applications because of the high gain and high frequencies of operation. The production MESFET can obtain a cut-off frequency, f_T, greater than 25 GHz, while the PHEMT can reach greater than 100 GHz. The current controlled HBT typically has f_T in excess of 50 GHz with relaxed lithography demands.

GaAs-based optical detectors are ideal for 850 nm operation with absorption up to 870 nm due to the direct energy bandgap. Also, the high absorption coefficient, α, provides high efficiency photodiodes. The AlGaAs/GaAs material system produces 850 nm sources, Light Emitting Diodes (LEDs) at low speeds and Vertical Cavity Surface Emitting Lasers (VCSELs) at higher speeds. The VCSEL device structure also has high optical power levels and low threshold voltages with circular emission from the wafer surface and a planar fabrication process.

The cost and performance trade-offs between these devices are well known, but the key for OEICs is the feasibility of integrating several of these devices on one substrate. Several integration schemes have been demonstrated using both non-epitaxial and epitaxial materials. Of specific interest to Gigabit Ethernet systems are the integration of MSM photodiodes with ion implanted MESFET transimpedance amplifiers (TIA) [1-3], MSM photodiodes with PHEMT TIAs [4], PIN-TIA circuits [5,6], PIN-HBT circuits [7], VCSEL-FET circuits [8], and PIN-VCSEL ICs [9].

Further integration of advanced OEIC devices requires epitaxial materials and compatible fabrication processes. The epitaxial material used to produce one device can also be used to design other devices as well. Because of this material synergy the performance of some devices can be increased by integration of device types. This material synergy can also help to defray the costs of the required epitaxial materials.

III. Gigabit Ethernet Datacommunications

The Gigabit Ethernet datacommunications market has been driven by local area network proliferation in the business community. With increasing network traffic, the LAN has become the bottleneck in the communications link. Current implementation uses 10 Mbps Ethernet or 100 Mbps Fast Ethernet. Gigabit Ethernet is the extension of the IEEE 802.3 Ethernet standard developed for 1.25 Gbps communications [10]. This extension of the standard provides a 10-100 times increase in network speed. The Gigabit Ethernet standard covers multiple transmission schemes; 1000Base-SX (at 850 nm), 1000Base-LX (at 1310 nm) and 1000Base-T (over CAT5 wires).

This proliferation of the fiber optic LANs has opened the door for high speed, low cost GaAs-based OEIC circuits. Eventually, the Gigabit Ethernet standard could bring fiber optic LANs to every desktop. The extent at which the cost and performance needs are met will determine how widespread the fiber optic LAN will become.

The Gigabit Ethernet transceiver system diagram is shown in Figure 1. It is comprised of optical devices, and both analog and digital ICs. This generic system is independent of the chosen wavelength and the GaAs-based devices previously described are capable of supporting all of the required elements.

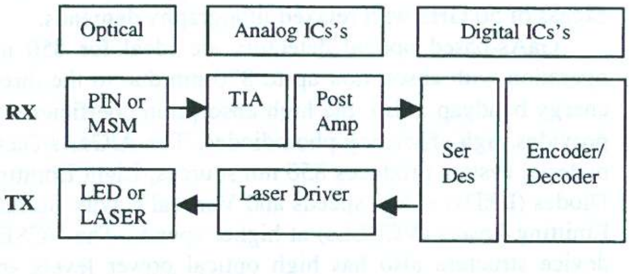

Figure 1: Gigabit Ethernet Transceiver System Diagram

The system front end requires a photodiode, laser or LED, and analog ICs consisting of a driver circuit and low noise TIA with a high gain post-amplifier. The back end is comprised of digital ICs which handle the data using Serializer/Deserializer and Encoder/Decoder circuits.

The fiber optic transceiver is used in local area network interface cards (NIC), switches, routers and hubs.

GaAs-based OEICs have enabled the implementation of the 1000Base-SX standard because of low cost, high performance front-end components. Specifically, the commercialization of the high reliability VCSEL and integrated MSM-TIAs has enabled the price of 1000Base-SX transceivers to drop below $100. The market forecast for Gigabit Ethernet transceivers is shown in Figure 2 along with corresponding prices. As the prices drop with higher volumes, a path of further integrating the components will help in reducing the costs.

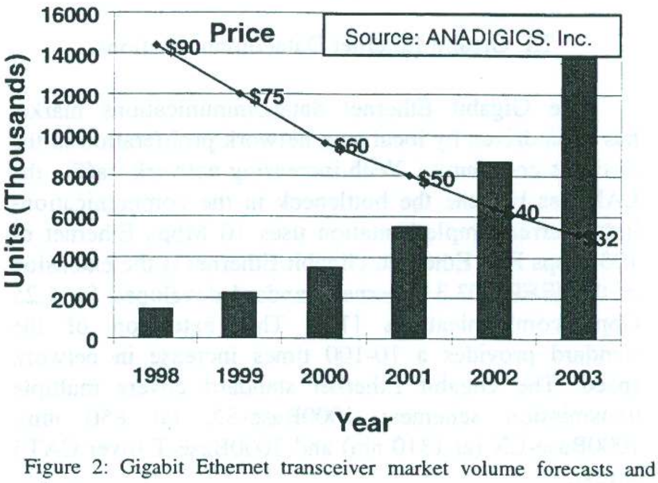

Figure 2: Gigabit Ethernet transceiver market volume forecasts and prices.

IV. GaAs OEIC Advantages

GaAs-based OEICs have several advantages as system integration increases. The properties of the circuits required in Gigabit Ethernet systems demand both high bandwidth analog capabilities as well as high speed digital capabilities of the electronic devices. Also, the ability to integrate optical devices set GaAs apart from Silicon.

Significant performance improvements are gained by integrating the photodiode and analog receiver front end. This has been demonstrated and is widely employed with cost and performance benefits. The cost savings arise in fewer separate components with lower total packaging and testing costs. Improved performance is due to elimination of additional bondwire capacitance and optimization of matching circuitry for the photodiode. Similar improvements can be realized in other areas of the system.

Integration of the system can either proceed vertically, integrating transmit and receive functions on one IC, or horizontally, in either the transmit or receive chain. Eventually, all components can be integrated onto one IC.

The integration of the different functions and devices has several distinct advantages. These advantages include:

- Synergy of epitaxial materials
- Facilitating on-wafer testing of both optical and electronic devices
- Elimination of multiple test cycles and packaging expenses
- Facilitating on-wafer functionality testing of transceiver components

As integration increases, epitaxial materials will be required to accommodate the fabrication of optical and electrical devices on one substrate. At the same time, it will be necessary to increase the speed and performance of both the optical and electrical epitaxial materials. The increased substrate costs will be offset by the value added by the additional functions. The synergy between the materials utilized for the optical and electrical devices will also facilitate higher performance devices and will allow for the integration of more of these different devices on one substrate. As the integration of the devices becomes more complex (i.e., photodiodes + lasers + FETs), the cost of the materials per part can be reduced.

Additionally, as planar optical and electronic devices are integrated, optical device testing can be performed at the wafer level. On-wafer testing of optical devices can reduce the cost by automating the test process and eliminating the need for costly packaging prior to testing. On-wafer testing has allowed for low-cost, high throughput MSM-TIA and VCSEL production employing techniques similar to high volume electronic semiconductor manufacturing. With further component integration, these techniques can be expanded to full on-wafer transceiver functionality testing. The total test and assembly costs will be significantly reduced as functional integration increases.

In typical systems, each optical and electronic component is separately tested and packaged. During the assembly process, the individual components are re-packaged and re-tested. Highly integrated OEICs reduce the number of assembly steps and test cycles, thereby further reducing the cost.

V. Gigabit Ethernet Optoelectronic Integrated Circuits

Several OEIC products are commercially available for the Gigabit Ethernet market. Integration has thus far been limited to the receiver front end and has taken the form of horizontal integration of the photodiode with the transimpedance amplifier.

The first GaAs-based OEIC to be applied to Gigabit Ethernet applications is the integrated MSM photodiode with a transimpedance amplifier operating at 850 nm and 1.25 Gbps. This integration has resulted in a high performance, low cost front end component. A photograph of this GaAs die is shown in Figure 3 (courtesy ANADIGICS, Inc.).

Power supply requirements for Gigabit Ethernet systems are migrating to 3.3 Volts for low power consumption. Low voltage power supplies (<5 Volts) typically do not provide enough voltage for the depletion mode circuitry employed in high speed analog GaAs ICs. To overcome these circuit limitations, a GaAs DC-DC negative voltage generator has been developed to facilitate the design of 3.3 Volt GaAs-based Gigabit Ethernet circuits [11].

The microwave DC-DC converter is designed with an oscillator frequency in the 4-10 GHz range. This high frequency allows for smaller capacitors placed on-chip and small circuit size for easy integration. Also the high frequency generated is out of band for the Gigabit Ethernet systems.

This microwave DC-DC converter has been used to develop the first 3.3 Volt integrated OEIC [12]. The 3.3 Volt MSM-TIA front end circuit meets all of the same performance specifications as the earlier 5 Volt design with a lower supply voltage. A block diagram of the circuit is shown in Figure 4.

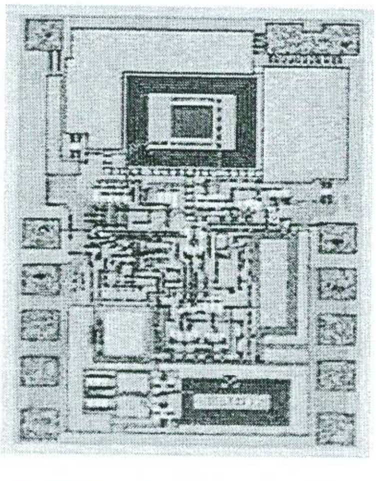

Figure 3: Photograph of integrated MSM photodiode with Transimpedance amplifier (courtesy ANADIGICS).

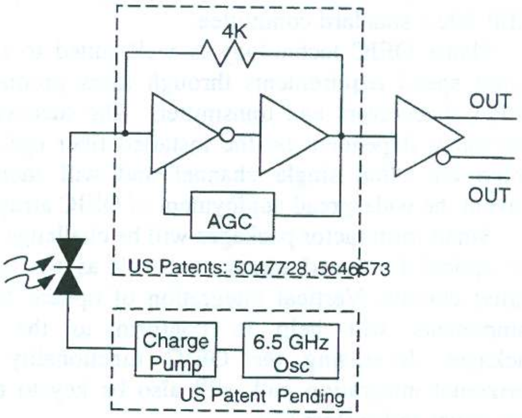

Figure 4: Block Diagram of 3.3V Gigabit Ethernet MSM-TIA.

The DC-DC converter is used to generate up to 4 Volts for a negative supply. This is used in the circuit to provide additional voltage margin for current supplies and photodiode bias.

Additional integration paths exist in the transmit function, combining VCSELs and laser drivers on one GaAs IC. Further horizontal integration requires additional digital circuit functionality to fit into the Gigabit Ethernet systems. The vertical integration of optical components is more complex and will most likely occur after significant horizontal integration occurs. These integration paths will rely extensively on advanced epitaxial materials.

VI. Future OEICs and high speed Ethernet Applications

As the Gigabit Ethernet market matures, new developments and technologies will enable better performance and lower costs. GaAs-based OEICs are poised to play a significant role in this growing market. Further integration could eventually lead to a full transceiver "system on a chip".

The developments that will define the role of GaAs-based OEICs in the Gigabit Ethernet market are the incorporation of epitaxially grown PHEMTs into OEICs and the migration to lower cost 6" GaAs substrates in manufacturing. PHEMT-based OEICs are emerging in the near future as a result of higher performance standards requiring advanced epitaxial materials. Transition to manufacturing on 6" GaAs substrates is in progress and will help to lower the cost per area of the ICs. This will make higher levels of integration more cost effective.

The challenges presented by the future generations of data communications standards are higher speeds, small form factor packages and different wavelengths of operation. The extension of the Gigabit Ethernet system to 2.5 Gbps data links has already been proposed. These will most likely remain proprietary systems since a formal specification is not expected for this data rate. The next significant data rate for LAN systems is 10 Gbps. Since most of the currently available optical devices and circuits are limited to operation less than 10 Gbps, this will require a significant amount of device development.

Standards at 10 Gbps are currently being developed in the IEEE 802.3 standard committee.

Planar OEIC technology is well suited to meet the higher speed requirements through mass production of arrays of receivers and transmitters. The success of this solution is dependent on the installed fiber optic cables which are often single channel and will most likely prevent the widespread deployment of OEIC arrays.

Small form factor packages will be challenge for both the optical front end circuits as well as the back end digital circuits. Vertical integration of optical front end components will help to conform to the smaller packages. Increasing the OEIC functionality in the horizontal integration path will also be key to reducing chip count and system size.

Long wavelength OEICs that are compatible with the 1000Base-LX standard at 1310 nm have already been demonstrated on GaAs substrates [13-15]. Because of the wider energy bandgap of GaAs, InGaAs is required for 1310 nm optical devices. InGaAs optical devices are compatible with InP substrates and are widely used in telecommunications systems, but are too costly for use in the high volume Gigabit Ethernet market. In order to increase the deployment of this wavelength standard, a significant amount of work is required to develop the materials and devices compatible with GaAs substrates.

VII. Conclusion

The future of GaAs-based OEICs for datacommunications at 850 nm looks very bright. Improvements in the devices, manufacturing and circuit design will all lead to better LANs at lower costs to the end user. Since the driving Gigabit Ethernet market factors are both price and performance, GaAs-based OEICs are well suited for these applications. GaAs also offers a good path forward for future implementations of data communications systems.

VIII. References

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