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Technological and Physical Compatibilities in Hybrid Integration of Laser and Monolithic Integration of Waveguide, Photodetector and CMOS Circuits on Silicon

Ming-Jing Zhou, Ton Ilkink, John Chalmers, Herma van Kranenburg, Hans Albers, Jisk Holleman and Paul Lambeck
MESA-Research Institute, University of Twente,
P.O. box 217, NL-7500 AE Enschede, the Netherlands

Jan Leendert Joppe, Herman Bekman and Ton de Krijger
TNO-FEL, P.O. box 96864, NL-2509 JG The Hague, the Netherlands

Abstract

In this paper, technological and physical compatibilities in hybrid integration of AlInGaP laser and monolithic integration of ZnO monomode waveguide, pin-photodetector, CMOS circuits for laser power control and signal amplification on silicon substrate are studied. Prospective problems and their possible solutions are discussed. Also experimental results are presented.

1. Introduction

Opto-electronic systems, based on complete integration of optical and electronic components on one single silicon chip, show many advantages due to compactness, rigidity, small size, the prospect of cheap batchwise mass production, low loss, high speed and avoidance of the need of alignment of optical parts and independent packaging. In this paper, we report results of the study of technological and physical compatibility for an optoelectronic integrated circuit (OEIC) in which however the light source is incorporated hybridically. This OEIC has to be considered as a general platform for integrated optical processing or sensing circuits.

The principal structure of the OEIC is shown schematically in Fig.1. Light, emitted from a laserdiode, is coupled into an integrated optical waveguiding system. A small part of the light is coupled into a photodiode by use of an optical interconnect function to control the laser output power. In addition it serves as a measure for the magnitude of the input signal of the optical circuit. The remaining light will continue to propagate in the waveguide and will be modulated in the optical circuits by the measurement. The optical output signal is totally coupled into a second photodiode. After amplification, the electrical signal is fed to the output. The ratio between output and sensor input signal is the outcome of the measurement, the exact relation depending on the specific optical circuitry that has been applied.
It has been decided to concentrate initially on systems with bandwidth < 10 KHz, high dynamic range and resolution. In a later stage, higher bandwidths (up to 100 MHz) will be put into focus. The applied wavelength will be 675 nm.

2. Technological Compatibility

The technologies used in this system include BiCMOS technology for the electronic circuits and the photodiode, optical interconnection technology, waveguide fabrication technology and laser mounting technology. Therefore, the technological compatibility should be studied and the prospective problems should be solved.

For the reasons of materials incompatibility at high temperature processing it is required that first all the electronic components including the photodiode are made, followed by the low temperature processes used for optical interconnections, the waveguide fabrication and the laser mounting. Thus compatibility problems were reduced to two main questions: (1) can degradation of microelectronics by subsequent optical technologies be avoided? (2) how to realise a microelectronics system, that is a good platform for the integrated optical parts?

The main results of our investigations are detailed in the next sections.

2.1 Influence of Waveguide Fabrication on Microelectronics

The low-loss, uniform planar waveguide, as shown in Fig.2, is made by reactive RF sputter deposition of ZnO [1] on the SiO₂ buffer layer. After deposition, the ZnO film is annealed at 400 °C for four hours to reduce the optical attenuation. Higher annealing temperatures should be avoided because they will cause contact failure in microelectronics. The channel of the ridge waveguide is etched by Argon sputter-etching.

A test chip containing diodes, capacitors and CMOS transistors was used to study the influence of the waveguide fabrication process on the microelectronics. Changes in leakage current, capacitance-voltage (CV) characteristics and threshold voltage were used to characterize the subsequent fabrication steps. The changes we observed were only minor and do not seriously alter the operation of the electronics. Zn diffuses quickly at 400 °C and it gives rise to mid-gap levels thus of leakage current observed may be explain that the solid solubility is

2.2 Influence of Laser Annealing in Waveguide Fabrication

The laser is an AlInGaP:Na + an anisotropically etched [2]. Multiple metal layers is pressed on the heated sub

The influence of laser annealing on microelectronics is now structures as mentioned, to investigate the process. There is a negative shift of MOS explained as contamination. This may be caused by a diffusion of Na + into the photoresist. More details will be given.

2.3 Realisation of Grating

In this OEIC system, an optical modulator is used as the light out of the waveguide in Fig.4. This grating waveguide. For higher wavelengths, an additional LOCOS layer is added [3] that will be used to realise the gratings. To realise that such an additional LOCOS for the microelectronics, the LOCOS in the BiCMOS need a minor adjustment.

2.4 Optical Buffer Layer

The waveguiding layer of silicon oxide must avoid Si-caused attenuation of the light out of the waveguide. Thick silicon is appreciated by the optical properties. The silicon thickness is thickness is required to be smooth as possible. Si + 1.0
2.2 Influence of Laser Mounting on Microelectronics

The laser is an AlInGaP ridge waveguide laser emitting at 675 nm. It is mounted epi-down in an anisotropically etched well by means of a thermocompression method as shown in Fig.3 [2]. Multiple metal layers are evaporated on the substrate, after which the gold coated laser is pressed on the heated substrate.

The influence of the laser mounting on the microelectronics is now under investigation. Similar test structures as mentioned in section 2.1 are used to investigate the process. The first experimental results show a negative shift of MOS threshold voltages. A probable explanation is contamination, especially from Na ions. This may be caused by aceton cleaning or handling of the chips or the photoresist developer which we found contains Na. More detailed experiments are still going on.

2.3 Realisation of Grating Structures

In this OEIC system, a grating system is used to couple the light out of the waveguide and into the photodetector as shown in Fig.4. This grating is realised by the etching of the waveguide. For higher wavelength a second grating has to be added [3] that will be realized at the surface of the silicon wafer. To realise that surface grating structure, we introduced an additional LOCOS field oxidation during the fabrication of the microelectronics, that is compatible with the standard LOCOS in the BiCMOS technology. Of course, the process conditions for the first LOCOS need a minor adjustment.

2.4 Optical Buffer Layer Structure

The waveguiding layer has to be separated from the Si by an optical buffer layer in order to avoid Si-caused attenuation of the light propagating through the waveguide. The buffer layer thickness is required to be larger than 1 μm. In addition, it is required to be as uniform and smooth as possible. Since the PLOX (plasma-oxide) layer in BiCMOS technology is not appreciated by the optical system due to its higher refractive index, we introduced an additional lithographic process step to delete the PLOX layer at the waveguiding circuitry area.

Now for the buffer layer, there are two options: (1) 0.5 μm BPSG (SiO2 doped with boron and phosphorus) + 1.0 μm CVD oxide. (2) 0.5 μm BPSG +1.0 μm sputtered oxide. After
ZnO deposition, it was found that only the second option results in an acceptable optical attenuation. Therefore, the sputtered oxide is a better basis for the ZnO growth.

3. Physical Compatibility

The integrated system is illustrated in Fig. 5.

In this system, the starting material is a p-epitaxial Si layer on a p⁺ substrate. The integrated circuits are made by standard BiCMOS technology. The advantages of BiCMOS technology include very low static power dissipation, excellent noise immunity, and low sensitivity to ionising particles, which is very important in optoelectronic applications.

Integration of optical and electronic components asks for a discussion of spurious interactions between them.

4.1 Isolation Between Laser and Substrate

The polarity of the laser diode in the epi-down configuration is not compatible with the silicon substrate; therefore an electrical isolation between the laser and the Si substrate is needed; there are three choices (1) laser mounted in a well inside the Si substrate, after sputtering of an additional SiO₂ layer. (2) laser mounted in a well inside the SiO₂ layer, automatically isolated by the remaining SiO₂. (3) laser mounted in a well inside the SiO₂ layer, isolated by an additional sputtered SiO₂ layer. After investigation, we concluded that the first option is the most practical because the others require thick oxide buffer layers (>2 μm) which may crack.

The electrical connection between the laser and the driver circuit can be realised by means of bonding wires.

4.2 "Cross Talk" Behaviour

The "Cross Talk" behaviour includes both the electronic and optical effects.

The electronic cross talk occurs mainly between the photodiode and the electronic circuitry. This effect is mainly caused by photon induced carrier diffusion in the substrate. To minimise or eliminate this interaction, a spatial separation and the introduction of a diffused guard ring is foreseen, as shown in Fig. 5.

The opto-electronic or waveguide channels. If absorbed in the Si, influence on the electronic system.

4.3 Thermal Behaviour

The thermal influence laser diode (120 mW) are two kinds of then heating of component instances a 2-D numeric system [4].

First, we studied the calculation was performed to calculate the maximum local temperature of the heating can be neglected in Fig. 6.

Fig. 6. Maximum temperature incident power for various...
The opto-electronic cross talk is caused by light, propagating in the ZnO layer, outside the waveguide channels. This scattered light originates from imperfect laser-waveguide coupling. If absorbed in the Si, it will influence the performance of the electronic devices. To eliminate influence on the electronic devices, we introduce a light-blocking layer to cover the microelectronics.

4.3 Thermal Behaviour Consideration

The thermal influence could be of great importance in the final OEIC. It is found that the laserdiode (120 mW dissipation) and the driver electronics are the main heat sources. There are two kinds of thermal problems which should be considered. One is the effect of self-heating of components. The other is the influence between different components. In first instance a 2-D numerical simulation was developed to study the temperature distribution in the system [4].

First, we studied the temperature rise due to the photon absorption in the photodiode. The calculation was performed for several wavelengths and power densities. It showed that the maximum local temperature $T_{\text{max}}$ is reached at the surface of the photodiode. Furthermore $T_{\text{max}}$ increases with the incident power density and decreases with the wavelength. The self-heating can be neglected if the incident power is less than 1 mW/µm² for $\lambda=675$ nm as shown in Fig.6.

Fig.6. Maximum temperature in Si as a function of incident power for various wavelengths.

Fig.7. Temperature distribution in the OEIC at its working state.

Fig.7 shows the simulation results of the temperature distribution across the entire chip (thickness 450 µm), assuming that it is surrounded by air. The heat transfer mechanism in air is convection. Both the power dissipations of the laserdiode and the driver circuit are assumed to be 90 mW. It was found that the variation of the temperature over the whole chip is small, this is due to the high thermal conductivity of Si. Note that the temperatures are between 40 -
50 °C above ambient. In practice, due to the use of a heat sink, the increase of temperature on the chip can be reduced significantly and will be less than 10 °C.

5. Conclusions

The technological and physical compatibilities of hybrid integration of laserdiode and monolithic integration of waveguide, photodetector and electronic circuits have been studied. Results show that all the prospective problems can be solved and negative influences can be eliminated or minimised by applying proper methods and techniques.

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7. References


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1 Introd

In many fi detect low sensitivity. These hav by the rela that for lo which rest avalanches its ionisatic. The absent resolution, low numb reading ou energy res fabrication sensors so integrated integrated drift senso In section conclusion