a problem. This was also tested separately using the 488 nm line of an argon ion laser. At a power level of 10 μ W, the beam was focused to a waist spot size of 10 μ m inside the sample and an aperture was inserted on the output side that blocked 50% of the power. This value of 50% remained constant up to the maximum power of 110mW.

Fig. 3 Second-harmonic power as function of input power

Fig. 4 Second-harmonic power as function of wavelength

The curves are shifted vertically for improved visibility
(i) experimental results
(ii) computation for crystal with domain-wall offset with standard deviation of 0.8 μ m; scale of y-axis is same as for experimental curve
(iii) computation for perfectly uniform crystal

In Fig. 4 the second-harmonic output is shown as a function of fundamental wavelength. The phase-matching peak has the bandwidth predicted by theory, slightly less than 0.2nm, demonstrating that the full length of the crystal is involved in the interaction. The conversion efficiency of 0.07%/Wcm is ~ 10 times smaller than the theoretical value for a perfectly periodic crystal. Note that we have normalised against the physical length of the sample, not an 'effective' length derived from the phase-matching bandwidth. It has been shown that for an independent random offset from the ideal domain-wall position with Gaussian distribution, a standard deviation of roughly 0.5 coherence lengths gives a tenfold reduction of output power [8]. In our case, this means 0.8 μ m, which seems quite reasonable judging from Figs. 1 and 2. Fig. 4 curve (ii) is the trace for a simulated crystal with a standard deviation of $\sigma = 0.8$ μ m. This displays both a shape and a reduction in peak efficiency that are similar to the experimental curve.

Conclusion: High voltage pulses, applied using liquid electrodes and a periodic photoresist pattern, produce effective periodic domain inversion in lithium niobate. The experimental third-order

phase-matching bandwidth of a 3.3mm bulk crystal was equal to the theoretically expected value, showing that the whole crystal took part in the conversion. The conversion efficiency was reduced to 10% of the theoretical value by a random variation of the domain-wall positions. These values are expected to improve when we develop our processing to first-order gratings.

Acknowledgments: Support was given to J. Webjörn by the Swedish Institute and to V. Pruneri by Politecnico di Milano.

© IEE 1994

22 March 1994

Electronics Letters Online No: 19940562

J. Webjörn, V. Pruneri, P.St.J. Russell, J.R.M. Barr and D.C. Hanna (Optoelectronics Research Centre, University of Southampton, Hants, SO9 5NH, United Kingdom)

References

- ARMSTRONG, J.A., BLOEMBERGEN, N., DUCUING, J., and PERSHAN, P.S.: 'Interactions between light waves in a nonlinear dielectric', *Phys. Rev.*, 1962, **127**, pp. 1918-1939
- WANG, W., ZOU, Q., GENG, Z., and FENG, D.: 'Study of LiTaO₃ crystals grown with a modulated structure: I. Second harmonic generation in LiTaO₃ crystals with periodic laminar ferroelectric domains', *J. Cryst. Growth*, 1986, **79**, pp. 706-709
- FEISST, A., and KOIDL, P.: 'Current induced periodic ferroelectric domain structures in LiNbO₃ applied for efficient nonlinear optical frequency mixing', *Appl. Phys. Lett.*, 1985, **47**, pp. 1125-1127
- JUNDT, D.H., MAGEL, G.A., FEJER, M.M., and BYER, R.L.: 'Periodically poled LiNbO₃ for high-efficiency second-harmonic generation', *Appl. Phys. Lett.*, 1991, **59**, pp. 2657-2659
- ITO, H., TAKYU, C., and INABA, H.: 'Fabrication of periodic domain grating in LiNbO₃ by electron beam writing for application of nonlinear optical processes', *Electron. Lett.*, 1991, **27**, pp. 1221-1222
- BURNS, W.K., MCELHANON, W., and GOLDBERG, L.: 'Second harmonic generation in field poled, quasi-matched, bulk LiNbO₃', *Conf. Blue-Green Lasers, OSA 1994 Tech. Dig. Ser.*, 1994, **1**, pp. 38-40
- CAMLIBEL, L.: 'Spontaneous polarization measurements in several ferroelectric oxides using a pulsed-field method', *J. Appl. Phys.*, 1969, **40**, pp. 1690-1693
- HELMFRID, S., and ARVIDSSON, G.: 'Influence of randomly varying domain lengths and nonuniform effective index on second-harmonic generation in quasi-matching waveguides', *J. Opt. Soc. Am. B*, 1991, **8**, pp. 797-804

Elimination or minimisation of optoelectronic crosstalk between photodiodes and electronic devices in OEIC on Si

M.-J. Zhou, J. Holleman and H. Wallinga

Indexing terms: Integrated optoelectronics, Minority carriers, Crosstalk

The optoelectronic crosstalk between photodiodes and electronic devices is observed and investigated in OEICs based on silicon. Results show that the phenomenon is closely related to the diffusion of minority carriers, generated by photon absorption. The crosstalk can be eliminated or minimised by either placing the electronic devices far from the photodiode, or by enclosing them with a reverse-biased guard ring diode.

Introduction: Optoelectronic integrated circuit (OEIC) systems, based on silicon substrate, are attracting more attention because they allow easy integration of optical, photonic devices with MOS and/or bipolar circuitry [1], which are being considered for a wide range of applications. The systems have many advantages such as compactness, rigidity, small size as well as the prospect of cheap batch mass production, low loss, high speed and avoidance of the need for aligning the optical sections and independent packaging. However, because the system is monolithically integrated on the same substrate, mutual influences, especially optoelectronic cross-

talk, become crucial elements that affect the system stability and reliability.

Fig. 1 Diagram of optoelectronic crosstalk between photodiode and electronic device in OEIC on Si substrate

Inset: crosstalk influence on the output characteristic of an n-MOSFET:

— without crosstalk
--- with crosstalk

We report the observation of optoelectronic crosstalk between the photodiodes and electronic devices in our OEIC system [1] as shown in Fig. 1. When monochromatic light with a photon energy greater than the silicon bandgap is coupled into the photodiode, the characteristics of the nearby electronic device change significantly. When the light vanishes, the device regains its original characteristics. This phenomenon degrades the performance of electronic circuits integrated in the system. In this Letter, the crosstalk is investigated by both experiment and simulation. In particular, a reverse-biased guard ring diode is used to minimise the crosstalk and its influence on the electronic devices. The results are presented and discussed.

Experiment: In this experiment, as shown in Fig. 1, the starting material is a p-type thin epitaxial silicon layer on a p+ substrate. The integrated electronic devices are made by standard BiCMOS technology. The pin-type photodiode is realised by shallow n+ ion implantation into the lightly doped epitaxial layer. The photodiode is reverse biased in operation, resulting in total depletion of the i region. To study the crosstalk and its influence, several resistors and MOS devices are placed at different distances to the photodiode. The devices are then divided into two groups, one of them being enclosed by a guard ring diode, made by deep n+ ion implantation, to minimise the crosstalk effect. The light, emitted from a laser diode, is coupled into the photodiode via fibre. The crosstalk phenomenon is studied by measuring the changes in the characteristics of the devices both with and without light incident on the photodiode.

Fig. 2 Change of current flowing through the resistor as a function of average distance to the photodiode under different conditions

○ 2mW, 830nm, without guard ring
● 1mW, 830nm, without guard ring
△ 1mW, 632.8nm, without guard ring
□ 1mW, 830nm, with guard ring

Results and discussion: The crosstalk and its influence are clearly exhibited by the change in the output characteristics, as shown in the inset in Fig. 1, in an nMOSFET located close to the photodiode. For comparison, the change in the current flowing through the resistor, as an indicator of crosstalk, with an applied voltage of 1 V, is measured under different conditions. The results are plotted in Fig. 2. We found that the current flowing through the resistor always increases when the light impinges on the photodiode, resulting from the crosstalk between the photodiode and the resistor. From Fig. 2, it can be seen that the crosstalk is proportional to the light incident power or the optical wavelength, and decreases exponentially with an increase in the spacing d between the photodiode and the resistor. The crosstalk can be neglected when the resistor is placed far from the photodiode. It can also be seen that the crosstalk, when the resistor is close to the photodiode, is significantly reduced when a reverse-biased guard ring diode is included. The reduction is found to be independent of the applied voltage to the guard ring. The same results are also observed for the MOSFET devices.

Fig. 3 Comparison of current density distribution between photodiode and sense diode with optical source

$\lambda = 800\text{nm}$, $P_{\text{inc}} = 1\text{mW/cm}^2$

— without guard ring
--- with guard ring

The higher incident light power causes stronger crosstalk because of the larger amount of photons absorbed in the silicon [2] for a fixed area. To analyse the crosstalk effect, a 2-D program MEDICI [3] is used for simulation. The simulation structure is illustrated in Fig. 3 in which there are three diodes: photodiode, guard ring diode and sense diode. All the diodes are reverse biased at 5V. Owing to lack of space, only the current density distribution is given in Fig. 3. The solid lines are for the case without the guard ring diode. We found significant current at the electrode of the sense diode that, in fact, draws part of the photogenerated current from the photodiode. A simulation study indicates that the current which collected at the sense diode is mainly the electron current and decreases with an increase in the distance to the photodiode. This corresponds with our experimental results.

From both the experimental and simulation results, the crosstalk can be explained by the fact that as the photon flux travels through the photodiode, electron-hole pairs are generated by photon absorption. The electron-hole pairs generated within the depletion region are immediately separated by the high field, but those minority charge carriers generated in the substrate will diffuse in all directions towards the depletion region. Some of the carriers, electrons in this case, may reach the neighbouring electronic devices, causing the crosstalk effect. With small wavelength, the

crosstalk becomes weak because more photons are absorbed within the depletion region and fewer minority carriers are generated in the substrate. Furthermore, because of recombination, the concentration of the minority carriers decays exponentially as they diffuse. This is the reason why the crosstalk can be eliminated by placing the electronic devices far from the photodiode, at several diffusion lengths.

However, such a method reduces the compactness of the OEIC system and therefore, a guard ring diode is introduced. The simulation result in this case is also shown in Fig. 3 by the dashed lines. Compared with the case without the guard ring, the current density at the sense diode is significantly reduced, which verifies the previous experimental results. Simulation also shows, not given here, that the closer the guard ring to the electronic devices, the more the crosstalk is minimised.

Conclusion: We have investigated the optoelectronic crosstalk between photodiodes and electronic devices in an OEIC system based on Si substrate. Results show that the crosstalk strongly depends on the diffusion of minority carriers, generated by photon absorption in the substrate. Sufficient spacing between the photodiode and the electronic devices or a reverse-biased guard ring diode to enclose the electronic devices can be used to eliminate or minimise the crosstalk. The presented methods are also used in handling the crosstalk problems between electronic devices and other types of photodetector based on semiconductor substrates.

Acknowledgments: The authors wish to thank T. Aarnink, H. Van Kranenburg for wafer processing and A. Kimmels for his help in the simulation. This work was supported by the Dutch Ministry of Economic Affairs via the IOP-Electro-Optics Project No. EO-TEL92.301.

© IEE 1994

Electronics Letters Online No: 1994/0615

21 March 1994

M.-J. Zhou, J. Holleman and H. Wallinga (Department of Electrical Engineering, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands)

References

1. ZHOU, M.-J., IKKINK, T., CHALMERS, J., HOLLEMAN, J., WALLINGA, H., and LAMBECK, P.V.: 'A new technology for hybrid integration of lasers, waveguides, photodetectors and ICs on silicon'. Proc. ISLOE'93, Singapore, pp. 425-429, Nov. 1993
2. SZE, S.M.: 'Physics of semiconductor devices' (John Wiley & Sons, 1981), pp. 754-760
3. 'MEDICI - Two dimensional semiconductor device simulation'. Technology Modelling Associates, Inc., March, 1993

Integrated three channel laser and optical multiplexer for narrowband wavelength division multiplexing

C.M. Ragdale, T.J. Reid, D.C.J. Reid and A.C. Carter

Indexing terms: Integrated optoelectronics, Semiconductor junction lasers, Wavelength division multiplexing

The fabrication and characterisation of a monolithically integrated three channel narrowband wavelength multiplexer and DBR laser are reported. The multiplexers include Bragg gratings with an extinction ratio of > 20dB and a bandwidth of ~1nm to give channel spacings of < 10nm.

Introduction: Optoelectronic integration offers a route for achieving low cost components for broadband-ISDN subscriber systems. In addition, optoelectronic integrated circuits (OEICs) offer advantages in small size and improved temperature and mechanical stability which leads to greater reliability. The increasing demand for extra capacity on optical networks has led to the development of wavelength division multiplexing (WDM) and

dense WDM techniques to make more use of the large bandwidths available in optical fibres. This has led to the need for components which can perform the multiplexing/demultiplexing operations while also being low cost for inclusion in subscriber systems. In this Letter we report the fabrication of a three channel narrowband multiplexer OEIC consisting of two narrowband wavelength multiplexers integrated with three DBR lasers. The channel spacing of the multiplexer is ~5nm which is suitable for high density WDM systems.

Fig. 1 Schematic diagram of three-channel narrowband WDM device

Design and fabrication: A schematic diagram and photograph of the three channel narrowband WDM chip are shown in Figs. 1 and 2, respectively. The design is based on a single-channel add-drop wavelength multiplexer reported earlier [1]. Two add-drop multiplexers operating at wavelengths λ_1 and λ_2 are combined in series along with a third laser operating at λ_3 . The output from the first laser operating at λ_1 is split equally by the first 3 dB coupler and is reflected by a Bragg grating with matching Bragg wavelength λ_1 . If the round trip path lengths in the two arms of the coupler are identical, all of the reflected light will exit the device at the output port, port 2. Similarly, the output from the second laser, operating at λ_2 , is reflected by the matched grating 2 and enters the first add-drop multiplexer at port 3. Because the wavelength λ_2 is not at the resonance wavelength of Bragg grating 1 the light entering port 3 is crosscoupled by the Mach-Zehnder into output port 2. The output from the laser operating at wavelength λ_3 does not match the Bragg wavelength of either of Bragg gratings 1 or 2 and is crosscoupled by the two Mach-Zehnders to output port 2. Successful operation of this device relies on close matching of laser wavelengths λ_1 and λ_2 to the Bragg reflection band of the corresponding WDM grating. This is achieved by using a DBR laser structure in which the grating is defined at the beginning of the Mach-Zehnder waveguide. The gratings for the laser and multiplexer can thus be defined at the same time and in the same waveguide structure ensuring matching of Bragg wavelengths.

Integration between the active laser region and the rib waveguide WDM devices was achieved by a butt coupled selective growth approach [2]. The laser source wafer comprised a 2μm thick *n*-type InP buffer layer, a 0.15μm wavelength composition, undoped InGaAsP active layer and a 0.25μm thick, 1.3μm wavelength composition *p*-type InGaAsP guide layer. The waveguide region was grown by selective area low pressure MOVPE with undoped 0.6μm thick InP buffer layer, 0.35μm thick, 1.15μm composition InGaAsP guide layer and a 0.3μm thick InP cladding layer. The vertical optical coupling efficiency calculated by beam propagation modelling for this structure is > 80%.

First order gratings for the DBR lasers (50μm long) and the multiplexer gratings (1mm long) were defined using a two beam interference pattern from a UV laser. A step and repeat process was used to define the three different Bragg gratings in a single process. The gratings were etched to a depth of 0.14μm using methane/hydrogen reactive ion etching. This depth was chosen to give a peak Bragg reflection of ~100% with a bandwidth of ~1nm for the 1mm long WDM grating and a reflection of ~30% for the 50μm long laser grating [3]. Rib waveguides were then etched to form the Mach-Zehnder interferometers and a second MOVPE selective area growth was carried out to form the laser guide/electrical blocking layers. After metallisation a back facet was etched