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Citation for published version (APA):
Shen, L., Veldhoven, van, P. J., Jiao, Y., Dolores Calzadilla, V. M., Tol, van der, J. J. G. M., Roelkens, G., & Smit, M. K. (2015). Low optical loss n-type ohmic contacts for InP-based membrane devices. In P. Kockaert, P. Emplit, S.-P. Gorza, & S. Massar (Eds.), *Proceedings of the 20th Annual Symposium of the IEEE Photonics Benelux Chapter, 26-27 November 2015, Brussels, Belgium* (pp. 47-50). OPERA-photonics, Brussels School of Engineering.

Document status and date:
Published: 01/01/2015

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Low optical loss n-type ohmic contacts for InP-based membrane devices

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It is a key challenge for membrane photonic devices to have ohmic contacts with both low optical loss and low contact resistance. In this paper, we present novel n-type ohmic contacts to InP-based membranes based on AgGe, showing low absorption loss and good thermal stability. By using heavily doped InGaAs(P) as contact layers, annealing-free ohmic contacts with specific contact resistances in the level of $10^{-7}\ \Omega\ cm^2$ *are obtained. Furthermore, strong bandfilling effects in these contact layers result in low optical absorption. Compared to conventional AuGeNi contacts, this new solution gives an order of magnitude reduction in the propagation loss measured in membrane waveguides.*

Introduction

Recent developments in membrane photonics make it a promising technology for IIIV/Si hybrid integration [1]. In order to fabricate high performing devices, some technological challenges need to be addressed. As an example, ohmic contacts on top of thin membranes (usually n-type) require improved properties in both electrical and optical aspects. On the one hand, their contact resistances has to be reduced to reach high bandwidth and low power consumption. On the other hand, low optical loss from these contacts is required for membranes with sub-micron thickness.

Conventional AuGeNi-based n-type contacts provide very low contact resistance after annealing [2]. However the high optical absorption of Ni will limit its use in membrane photonic devices. More critically, the annealing process will lead to metal spiking as a result of Au diffusion at high temperatures. When it comes to membrane photonic devices, the spiking of metals into the semiconductor layers underneath can cause very high optical losses. An alternative approach by using AgGe-based contacts is proposed [3]. The use of Ge instead of metal as the first deposited layer provides a low optical absorption loss. Moreover, by replacing Au with Ag, the thermal stability of the metal contact is significantly improved due to a higher eutectic temperature (651 °C) of the AgGe alloy compared with that of AuGe (361 °C). The spiking effect in Au-based contacts is therefore reduced in the Ag-based solution. In this paper, we summarize the electrical and optical properties of this new contact. InP and its ternary and quaternary alloys are investigated separately as semiconductor contact layers.

Contact resistance

The specific contact resistance of the AgGe contact is characterized using the circular transfer length method (CTLM) [4]. Samples are prepared containing different contact layer materials: InP, InGaAs and InGaAsP. The InGaAsP quaternary alloy has a bandgap wavelength of 1.25 µm (hereafter referred to as Q1.25). These contact layers are 100 nm thick and are grown on top of Fe-doped semi-insulating InP (100) substrates using Metal-Organic Chemical Vapor Deposition (MOCVD). The doping concentrations are characterized using an electrochemical C-V profiler. Higher doping levels are obtained in InGaAs and Q1.25, due to the higher solubility of Si (n-type dopants) in these materials. The preparation procedures of these samples in the experiment can be found in [3].

The measurement results are summarized in Table 1. For comparison, the result of AuGeNi on InP is included [2]. Before annealing, samples with a 2 nm Ge layer show ohmic behavior, which is assumed to result from the tunneling current through the thin barrier of the 2 nm Ge layer. After annealing, all of the samples show ohmic behavior and the contact resistance reduce significantly. The contact on InP with 30 nm Ge shows lower resistance after annealing compared to that with 2 nm Ge, indicating the role of Ge in the reduction of contact resistance. Ge is supposed to increase the doping of the top surface of the n-InP layer after annealing [2], thereby reducing the contact resistance. In heavily doped materials (InGaAs and Q1.25) this effect is not visible. The current flow in heavily doped semiconductor contacts is governed by the field emission mechanism [5], for which the contact resistance depends strongly on the doping concentration. Therefore, the contact on Q1.25 with the highest doping provides the lowest contact resistance. The annealing-free AgGe contact on Q1.25 gives a contact resistance value close to that from conventional AuGeNi, providing a very favorable candidate for membrane devices, as it fundamentally avoids any high temperature related degradation.

Table 1. Specific contact resistances

Metals	Contact material and doping level (cm^{-3})	Thickness Ge (nm)	Specific contact resistance (Ω cm^2)	
			Before annealing	After annealing
AuGeNi	InP: 2×10^{18}	50	Non-Ohmic	1.0×10^{-7}
AgGe	InP: 2×10^{18}	2	5.6×10^{-4}	2.6×10^{-5}
		30	Non-Ohmic	1.5×10^{-6}
AgGe	InGaAs: 2×10^{19}	2	7.2×10^{-7}	1.4×10^{-7}
		15	Non-Ohmic	1.9×10^{-7}
AgGe	Q1.25: 5×10^{19}	2	2.4×10^{-7}	4.4×10^{-8}
		15	Non-Ohmic	4.2×10^{-8}

Contact optical loss

In order to evaluate the optical performance of the newly developed contacts, the optical loss introduced by the contact layers need to be studied. This is particularly important for InGaAs, which has a bandgap of 0.74 eV, smaller than the photon energy at 1.55 µm. In n-type heavily doped semiconductors, however, a reduction of absorption near the bandgap occurs, which has been explained with the bandfilling effect. By using the model described in [6], a low optical loss coefficient is predicted for InGaAs doped at 2×10^{19} cm^{-3} (see Figure 1). Standard optical loss measurements [3] using membrane WGs containing an InGaAs contact layer are performed, giving a strongly reduced material absorption coefficient for n-InGaAs of around 300 /cm. The higher value compared to the modeling results is assumed to be due to overestimation of the bandfilling effect in the model. For Q1.25, the absorption is mainly due to free carriers, as its bandgap energy is much larger than the photon energy at 1.55 µm.

Contacts with different lengths are patterned on top of the WGs to measure the optical loss resulting from the metal contacts. Samples with different contacts are prepared (see Table 2). The thickness of Ge in Sample B is 30 nm which gives the lowest contact resistance on InP, while in Sample C and D only 2 nm of Ge is used as this provide sufficiently low resistance. Details of the process flow and the measurement can be found in [3]. The normalized propagation losses at 1.55 µm are plotted in Figure 2. The corresponding loss coefficients extracted from the linear fitting are shown in Table 2.

Before annealing, contacts based on AgGe show much lower losses compared to those based on AuGeNi, due to the absence of Ni which has a high absorption coefficient. After annealing, AuGeNi contacts show a remarkable increase of loss, as a result of the spiking effect. AgGe contacts on InP also show a factor of 3 increase of loss, which could be related to some small spikes observed in the Ge layer or the Ge diffusion during annealing [3]. However, since the spikes cannot penetrate into the WG layers, the propagation loss is much lower compared to AuGeNi. In terms of AgGe contacts on InGaAs and Q1.25, they show only a slight increase (about 10%) of the propagation loss after annealing, which is in strong contrast to the other samples. This may be related to the reduction of the Ge thickness, as spiking and diffusion will be very limited with only 2 nm Ge. Meanwhile, the contact resistance of these contacts are also sufficiently low thanks to the highly doped contact layers. In short, the annealing-free ohmic contact based on AgGe/Q1.25 gives the lowest loss before annealing; it also shows a good thermal stability for high temperature processes.

Conclusions

A low-loss and low-resistance ohmic contact based on AgGe is proposed for InP-based membrane photonic devices. By using heavily doped contact materials, annealing-free ohmic contacts with contact resistances in the level of 10^{-7} Ω cm^2 are obtained. The optical properties of these materials are studied, showing strong bandfilling effect and low absorption loss. Combined with the low optical loss of AgGe, a massive reduction of the propagation loss in membrane waveguides is observed compared to conventional AuGeNi contacts. An additional advantage is the minimal influence of thermal treatments during the processing, leading to very stable and highly performing contacts.

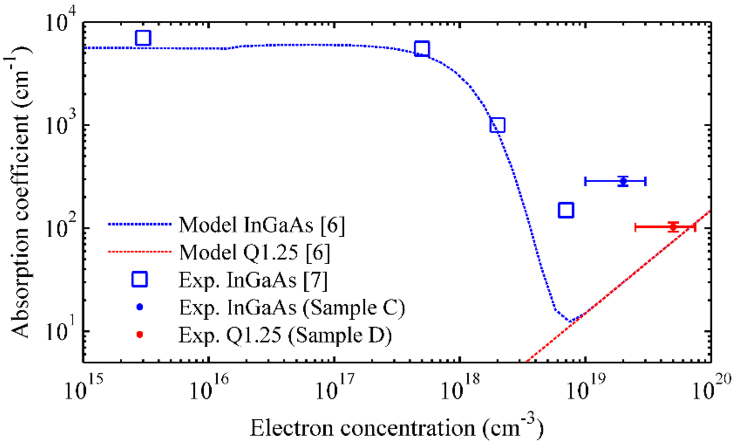

Figure 1. Absorption coefficient of InGaAs and Q1.25 at 1.55 µm versus electron concentration.

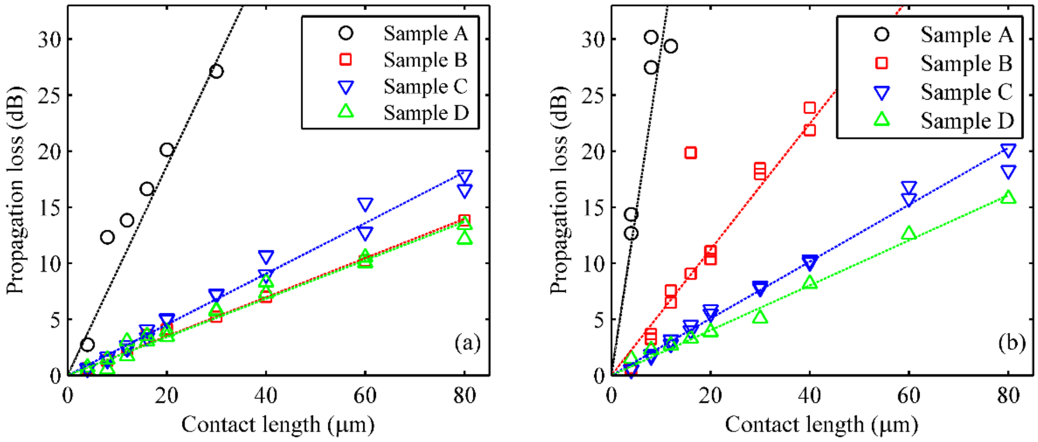

Figure 2. Propagation loss from different contacts versus contact length, measured before (a) and after (b) annealing.

Table 2. Propagation loss coefficients

Sample	Contact type	Propagation loss coefficient (dB/µm)	
		Before annealing	After annealing
A	AuGeNi/InP	0.93	2.91
B	AgGe/InP	0.18	0.56
C	AgGe/InGaAs	0.23	0.25
D	AgGe/Q1.25	0.17	0.19

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