Characterization of Ge/Ag ohmic contacts for InP based nanophotonic devices

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L. Shen, C.W.H.A. Wullems, P.J. van Veldhoven, V.M. Dolores Calzadilla, D. Heiss, J.J.G.M. van der Tol, M.K. Smit and H.P.M.M. Ambrosius

Eindhoven University of Technology, COBRA, Den Dolech 2, 5612AZ Eindhoven, The Netherlands

Low-resistance ohmic contacts with low optical absorption are needed for photonic devices with small volume, low power consumption and high bandwidth. Metal contacts consisting of a thin germanium layer below a silver layer promise low absorption losses. This makes them suitable for membrane and plasmonic photonic devices. Here we present electrical characterization of Ge/Ag ohmic contacts on n-type InP. A specific contact resistance of 1.5×10^{-6} Ωcm^2 is achieved by optimizing Ge thickness and annealing conditions. Next, highly doped InGaAsP-alloys have been investigated for further reduction of the contact resistance; specific resistances in the order of 10^{-8} Ωcm^2 are obtained.

Introduction

Electrically-pumped small-size devices are of great importance for photonic integration based applications. In order to obtain high performances of these devices, the contact technology needs to be optimized both electrically and optically.

InP Membrane on Silicon (IMOS) technology provides a integration platform for a full set of components with ultra-small size [1,2]. These devices are fabricated in an InP-based membrane which is bonded to a silicon wafer by using benzocyclobutene (BCB). In contrast to conventional InP-based devices, the top contact of an IMOS device is typically n-type. This is because with Metalorganic Chemical Vapour Deposition (MOCVD) the InP wafer is usually grown from n-side to p-side to minimize the diffusion of Zn (the p-type dopant). After flip-chip bonding and substrate removal, the n-type contact is deposited on top of the device structure. In these devices, a good n-type ohmic contact with low resistance is required to achieve high bandwidth and low power consumption. Furthermore, the optical loss from the metal contacts needs to be minimized, so that the contacts can be placed close to the active devices, thereby reducing series resistance without excessive loss for the guided optical modes.

Ni/Ge/Au-based ohmic contact to n-InP is a standard in conventional electronic devices due to its very low contact resistance after annealing [3]. However, when it comes to optical devices, the absorption loss from Ni is too high. This is because both the refractive index and the absorption coefficient of Ni are high. (This is in contrast to Ge, Au and Ag, of which either the refractive index or the absorption coefficient is much lower. See Table 1) In addition, it is well known that in Au based contact the annealing process will lead to metal spiking as a result of Au diffusion at high temperature [3]. The spiking of metals into the InP membrane underneath can cause high optical loss and a large leakage current.

Recently, Ge/Ag-based metal contacts emerge as a solution in plasmonic photonic devices due to its low optical loss and good adhesion to InP related materials [2].

Furthermore, the alloy formed by Ge and Ag also shows much better thermal stability than the Ge/Au based alloy [4], and therefore the spiking problem may be avoided. These features make Ge/Ag a very promising contact from the optical point of view. The electrical performances of this type of contact to InP related materials then becomes an interesting topic and will be the focus of this paper.

Material	Refractive index	Absorption coefficient (/cm)
Ni	3.438	546100
Ge	4.27	460
Ag	0.410	814600
Au	0.583	986400

Table 1. Optical properties of materials used in n-type ohmic contacts [5]

Contact resistance

Firstly, the specific contact resistance of Ge/Ag is characterized with the so-called circular transfer length method (CTLM) [6]. The samples in the experiment are a Fe doped semi-insulating InP (100) substrate with a 100 nm thick n-InP contact layer grown by MOCVD. This n-InP layer is doped to a level of 2×10^{18} cm^{-3} with Si. First, Ge is deposited on the top of the n-InP layer by electron beam evaporation, followed by the deposition of 300 nm of Ag. Four samples with different amount of Ge have been processed. Each sample is cleaved into several parts to test different annealing temperatures. The annealing is performed with a rapid thermal process for 30 seconds.

The measurement results are summarized in Figure 1. All of these samples show dependences of their specific contact resistances on the annealing temperatures. Before annealing, only the sample with 2 nm of Ge shows ohmic behavior. We think this is because the tunneling effect is sufficiently strong with such a thin Ge layer. All of the samples show ohmic behavior after annealing to 300 ºC, and their resistances reduce further with higher temperature annealing. The optimal range is between 350 ºC to 400 ºC, which is similar to Ni/Ge/Au based contacts. The effect of Ge on the contact resistance is also seen in these plots. Ge is supposed to increase the doping of the top surface of the n-InP layer after annealing [4], thereby reducing the contact resistance. In our experiments, the sample with 30 nm of Ge shows the lowest value after annealing. The sample with more Ge (50 nm) does not improve, probably because it blocks the physical contact between Ag and InP even with annealing. The lowest value of 1.5×10^{-6} Ωcm^2 is obtained from the sample with 30 nm of Ge and 400 ºC of annealing. This value makes this ohmic contact suitable for a large range of applications.

Metal spiking

In order to compare the spiking behavior of the Ge/Ag contact and the Ni/Ge/Au contact, cross-sectional SEM pictures are taken to show the metal-InP interfaces after 400 ºC annealing (Figure 2). The Ni/Ge/Au contact produces a very rough interface. The metals and alloys penetrate over 150 nm into the InP layer. In contrast, the Ge/Ag contact shows a sharp interface without any presence of spiking. This is believed to be a result of the much higher eutectic temperature of Ge-Ag alloy (651 ºC) compared to that of Ge-Au alloy (361 ºC) [4]. The spiking-free Ge/Ag contact has advantages in membrane devices in which the optical mode is very close to the metals.

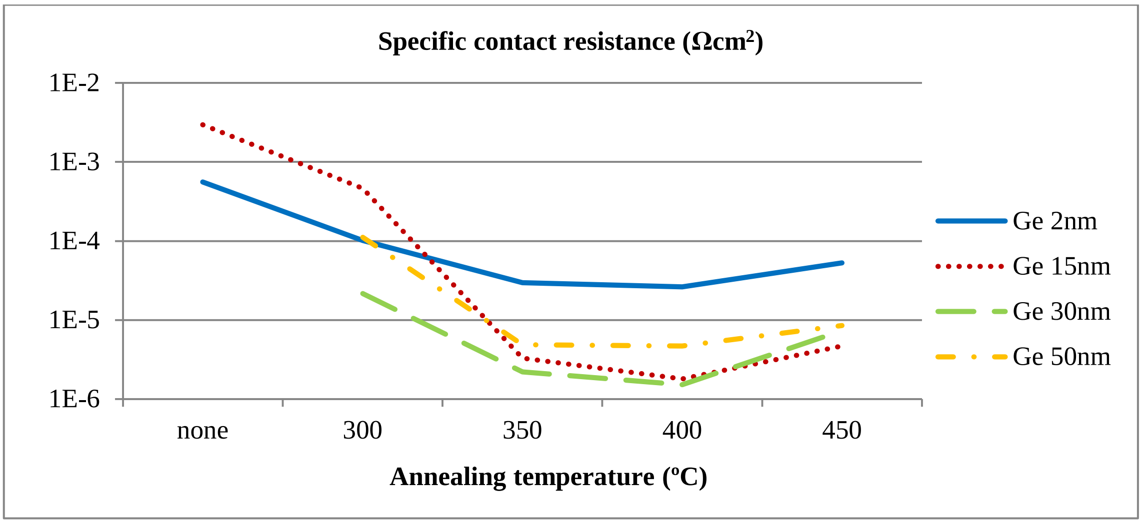

Figure 1. Specific contact resistance of Ge/Ag contact to n-InP

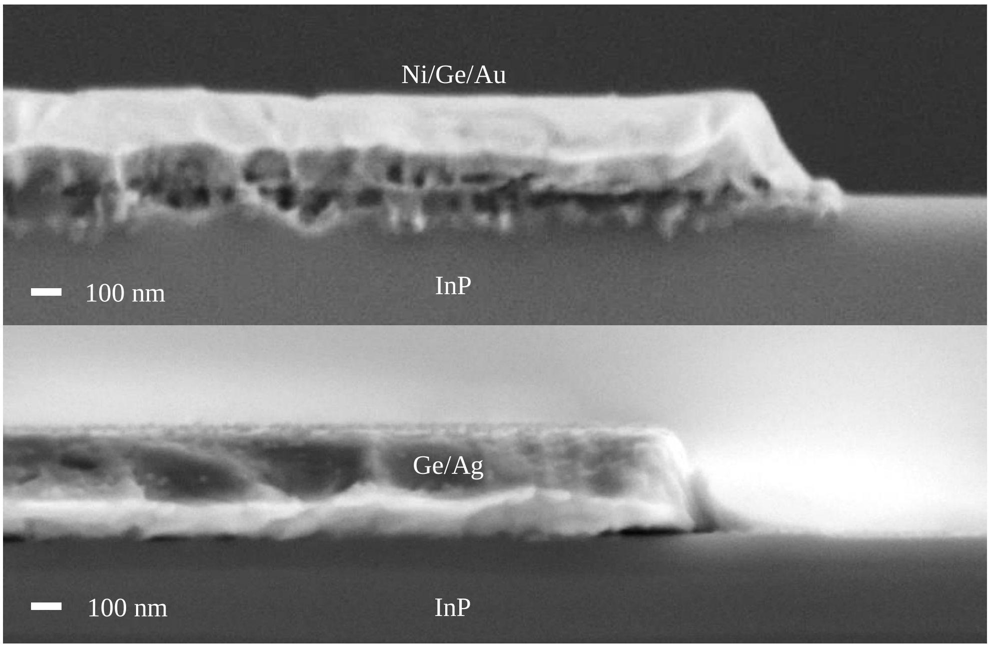

Figure 2. Cross-sectional SEM photos of metal/InP interface after annealing

Contact on highly doped material

Materials with a smaller bandgap like InGaAs are also used in electronics enabling ultra-low resistance non-alloyed ohmic contacts [3]. The low bandgap usually leads to a surface Fermi level that is pinned in the conduction band, which is ideal for an n-type ohmic contact. Besides, these materials can be doped much higher than InP, which results in a stronger tunnelling mechanism and therefore a lower contact resistance. In our work, we focus on InGaAsP, which has a larger bandgap than InGaAs, in order to prevent the high optical loss due to interband absorption. Since most of our applications focus on a wavelength of 1.55 µm, we choose the InGaAsP (lattice matched to InP) with a bandgap of 1.25 µm. The test sample has the same structure as the one used in the electrical measurement mentioned above, but now the n-InP layer is replaced by an n-InGaAsP layer. In this test, the InGaAsP is doped to a level of 5×10^{19} cm^{-3} with Si. Two samples with 2 nm and 15 nm of Ge are prepared. The CTLM measurement results are shown in Figure 3. After annealing beyond 300 ºC, all the contacts provide resistances lower than 10^{-7} Ωcm^2. These extremely low specific contact resistances make this contact suitable for ultra-small photonic devices even with nanometre size. Furthermore, the sample with 2 nm of Ge provides a low contact resistance of 2.4 ×10^{-7} Ωcm^2 even without annealing. This non-alloyed contact solution is useful in certain applications in which a high temperature process is not allowed. For instance, in the IMOS technology, the polymer material used in the bonding process (BCB) usually starts to degrade above 325 ºC which causes problems to the membrane devices. In fact, for most devices containing polymer materials, a non-alloyed low-resistance contact is of key importance.

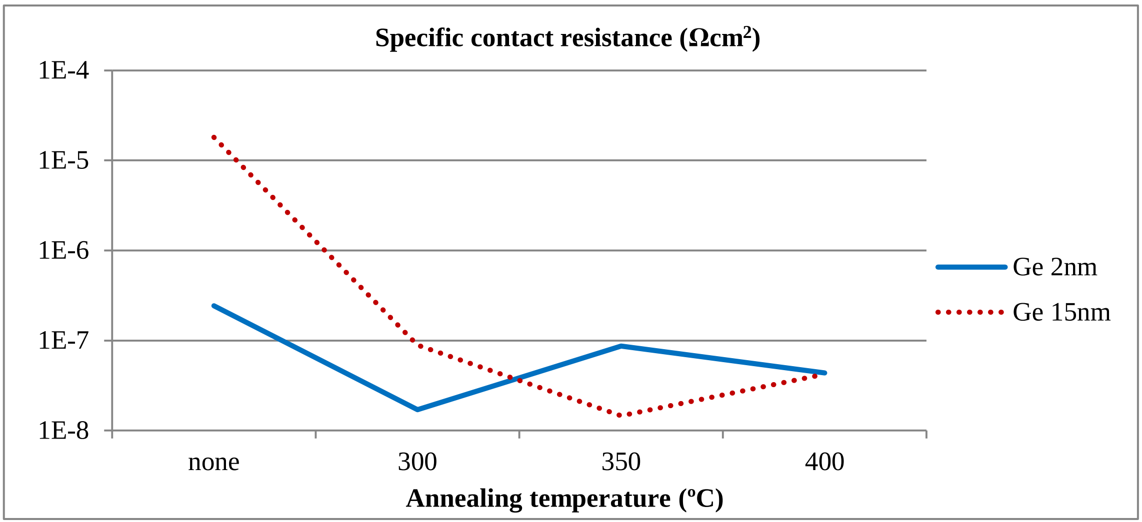

Figure 3. Specific contact resistance of Ge/Ag contact to highly doped InGaAsP

Conclusions

A low resistance Ge/Ag based n-type ohmic contact to InP related materials is developed and characterized. The Ge thickness and the annealing conditions are studied and optimized to minimize the specific contact resistance. Very low resistances of 1.5×10^{-6} Ωcm^2 to InP and 1.5×10^{-8} Ωcm^2 to InGaAsP are achieved. Compared to conventional Au based contacts, the Ge/Ag based contact also shows better uniformity in the interface to InP. The spiking problem is avoided.

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