Pt/Ge/Au ohmic p-contacts with reduced optical loss for integrated opto-electronic devices

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This paper presents an investigation into a Pt/Ge/Au metallisation scheme for ohmic p-contacts on highly doped p-InGaAs, optimized for integrated opto-electronic devices. The scheme achieves contact resistances below 3×10^{-6} Ωcm^2 without annealing. The thickness of each metal layer is optimized specifically for loss reduction of a waveguide integrated UTC-PD using FDTD simulations, and reduces the optical loss compared to traditional Ti/Pt/Au schemes with 34%. The specific contact resistance and thermal stability are investigated by CTLM measurements for various thermal treatments. The proposed Pt/Ge/Au scheme is an interesting alternative for low-loss ohmic p-contacts for InP opto-electronic devices.

Introduction

Integrated opto-electronic devices are essential for various high performance applications in communication, sensing and computing [1]. In particular for opto-electronic devices in nanophotonic platforms such as silicon-on-insulator and indium-phosphide (InP) membranes, electrical contacts can be positioned in close proximity to the optical mode, requiring low loss metals [2], [3].

The traditional titanium, platinum and gold (Ti/Pt/Au) metallisation scheme for III-V materials, although widely used [4], [5], suffers from high optical absorption and requires annealing to achieve contact resistances below 1×10^{-5} Ωcm^2 [5]. The high optical absorption combined with material intermixing from annealing can lead to detrimental optical losses in miniaturized integrated devices. This work proposes a platinum, germanium & gold (Pt/Ge/Au) metallisation scheme for doped p-InGaAs, which aims to provide a low optical loss alternative to the Ti/Pt/Au scheme by using thin high work function platinum as the initial layer [6] a low optical-loss germanium intermediate layer [3] and a corrosion-resistant final gold layer [4]. Pt/Ge/Au contacts have been reported as n-contact in combination with n-GaAs layers, only leading to ohmic contacts after annealing at 450°C or above, for 15 minutes [7].

The proposed Pt/Ge/Au scheme results in ohmic p-contacts with a specific contact resistance below 3×10^{-6} Ωcm^2 suitable for integrated opto-electronic devices. The scheme is optimized to be used in high speed uni-travelling carrier photodetectors (UTC-PDs) [8] as depicted in Fig. 1 and demonstrates an optical loss reduction of 34% compared to a traditional Ti/Pt/Au scheme, based on FDTD simulations. Circular transfer length method (CTLM) measurements are used to determine the contact resistance and thermal stability of the contacts fabricated on a highly doped p-InGaAs layer on an InP substrate.

P-contact requirements

The traditional Ti/Pt/Au metallization scheme applied to p-doped InGaAs ($\geq 1\times10^{19}$cm^3) can reach contact resistances as below 1×10^{-6} Ωcm^2 after annealing [6]. Titanium is used as the initial layer, as it provides good adhesion to the semiconductor surface [4]. Platinum is then used because of its inertness in combination with the ability to bond to

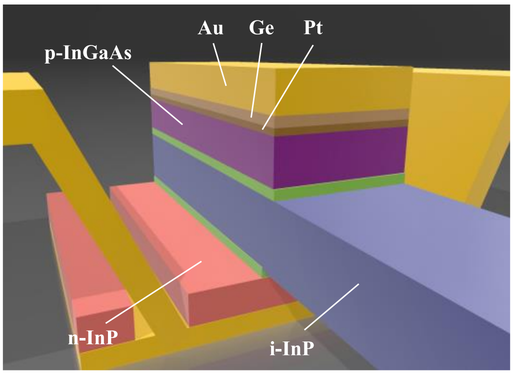

Figure 1: Schematic representation of a UTC-PD with Pt/Ge/Au p-contacts used for FDTD simulations.

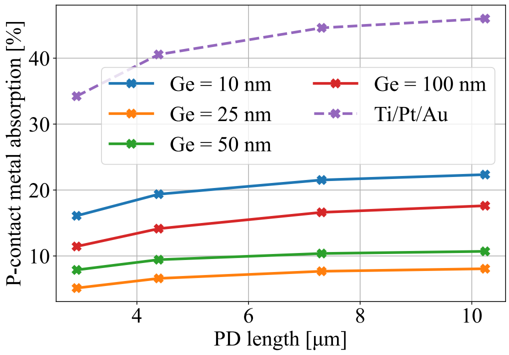

Figure 2: FDTD simulations showing minimised p-contact metal absorption for a Ge thickness of 25 nm.

the final Au layer [4]. Additionally, Pt limits the diffusion of Au due to its low Au diffusion coefficient. Gold provides extreme resistance to corrosion, which makes it very suitable to be used as the final metal layer. However, both Ti and Pt inherently have a high optical absorption coefficient. Contact resistance for p-type contacts can be reduced by using a high work function metal as initial metal layer, as this reduces the barrier height. P-type contacts using Pt as initial layer have demonstrated a reduced contact resistance with respect to contacts with Ti as initial layer [6], [9]. Although Pt exhibits high optical absorption, a thickness of only 5nm can be sufficient [9]. Additionally, Pt seems to provide sufficient adhesion to semiconductor layers based on the aforementioned reports. Gold maintains to be a good candidate as final metal layer due to the corrosion resistance. As intermediate layer, germanium (Ge) is considered to be a good candidate due to its low optical loss [3].

Optical loss optimization

The thickness of each of the layers is optimized for the case of a waveguide integrated uni-traveling carrier photodetector (UTC-PD) [8] using FDTD simulations. A schematic representation of the device is depicted in Fig. 1. The optical loss is determined based on the overlap of the optical field with the metal layers, combined with their respective absorption coefficients. To limit optical loss, it was decided to fix the Pt thickness to the minimum of 5 nm based on the results in [9]. The Ge thickness was swept from 10 to 100 nm and a comparison to the traditional Ti/Pt/Au metallisation scheme is provided. The simulated results are shown in Fig. 2 and demonstrate minimised losses for a Ge thickness of 25 nm, corresponding to an optimized optical field distribution inside the UTC-PD. Compared to a traditional Ti/Pt/Au (10/50/200 nm) scheme, a Pt/Ge/Au (5/25/200 nm) scheme can provide an average loss reduction of 34%, which is very significant for the optimization of opto-electronic devices.

Fabrication

The contacts are defined on a 3” InP wafer having a InGaAs p-contact layer with a doping of 2×10^{19} cm^3. Metal patterns are defined using electron beam lithography combined with a lift-off process. After resist development, a low power oxygen plasma was used as a descum step, followed by a 2 min wet cleaning step in H_3PO_4 to clean the p-InGaAs surface. The metals are deposited using an electron beam evaporator. Both the new Pt/Ge/Au and traditional Ti/Pt/Au schemes are defined on the same wafer sample, but in completely isolated processes.

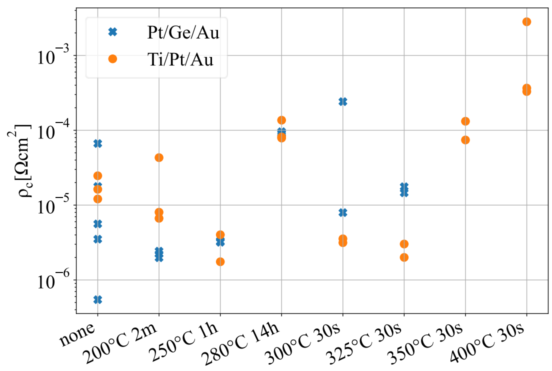

Figure 3: ρ_c for various thermal treatments for both Pt/Ge/Au and Ti/Pt/Au metallisation schemes.

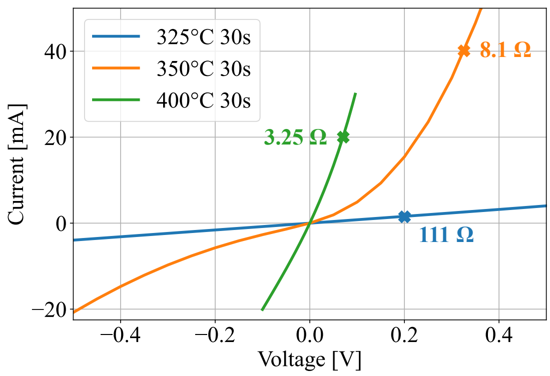

Figure 4: IV curves of a single CTLM ring for various RTA treatments

CTLM measurements

The circular transfer length method (CTLM) is used to determine the specific contact resistance of the contacts [10]. Both metallisation schemes are introduced to various thermal treatments, and multiple measurements have been performed across the wafer for each of the treatments. All CTLM measurement results are combined in Fig. 3 to provide a concise overview. The results show specific contact resistances below 1×10^{-6} Ωcm^2 can be reached for the Pt/Ge/Au stack deposited as is. Compared to the results for Ti/Pt/Au (ρ_c > 1×10^{-5} Ωcm^2), the new scheme is able to outperform the traditional scheme. However, the new scheme also clearly shows high variation in the values for ρ_c, indicating low stability directly after deposition.

Thermal stability

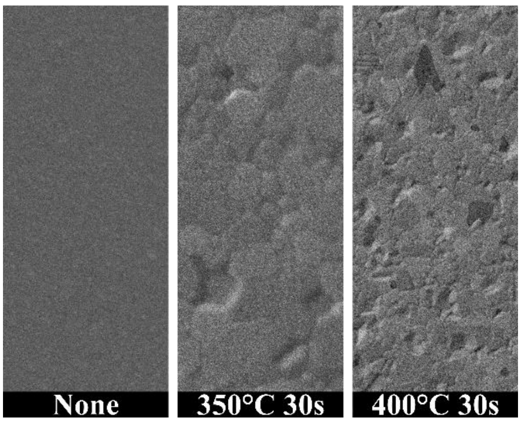

Figure 5: Pt/Ge/Au SEM pictures showing significant material intermixing for 30s RTA at 350°C and 400°C.

The contact resistances in Fig. 3 demonstrate ρ_c values ranging from 1×10^{-5} to 1×10^{-6} Ωcm^2 for thermal treatments up to 250°C. For an overnight treatment at 280°C both schemes approach a ρ_c as high as 1×10^{-4} Ωcm^2. This is in line with previously reported Pt-based metallisation schemes [11]. For RTA treatments up to 325°C, annealing still results in ohmic contact behaviour, although at increased contact resistances. For the Ti/Pt/Au scheme, RTA at 325°C reduces the contact resistance to values matching the Pt/Ge/Au scheme before treatment. Beyond 325°C, the Pt/Ge/Au scheme starts to show non-ohmic behaviour as visible in the IV-curves in Fig. 4. The resulting contact resistance decreases significantly and does not change as function of the CTLM ring size. SEM images reveal intermixing of the different materials starts to occur for RTA at 350°C and beyond as shown in Fig. 5. This dramatically reduces the contact resistance due to the formation of various GePt interfacial layers [12] in combination with diffusion of gold. Severe material intermixing is expected to have a detrimental effect on the optical properties of opto-electronic devices, which makes RTA unsuitable for the newly developed metallisation scheme.

Conclusions

This paper presents an investigation into a Pt/Ge/Au metallisation scheme for ohmic p-contacts on highly doped p-InGaAs, optimized for integrated opto-electronic devices. The scheme achieves low contact resistance without annealing and reduces the optical loss compared to traditional Ti/Pt/Au schemes. The optimal thickness of each metal layer is determined by FDTD simulations for a waveguide integrated UTC-PD structure showing that a Pt/Ge/Au (5/25/200 nm) scheme can provide an average loss reduction of 34%. The contact resistance and thermal stability of the Pt/Ge/Au scheme are investigated by CTLM measurements for various thermal treatments. The results show contact resistances below 3×10^{-6} Ωcm^2 without annealing, and remains ohmic for treatments up to 325°C. However, for higher temperatures, the scheme exhibits non-ohmic behaviour and significant material intermixing, which will degrade the optical properties of the contacts. The proposed Pt/Ge/Au scheme can be an interesting alternative to Ti/Pt/Au for low-loss ohmic p-contacts for InP opto-electronic devices, but further research needs to be done.

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