Optimization of electrical contacts in resonant tunneling diodes

Abstract: The aim of this work is to optimize the electrical contacts of the resonant tunneling diode. The influence of various factors on the specific contact resistance is investigated and a geometric calculation model of the series resistance is made. A Reduction of series resistance of almost 50% is achieved. Subsequently an increase in the frequency f_{max} of around 20% can be demonstrated.

I. Introduction

Nowadays, terahertz spectrum is becoming more and more important, which has many applications for instance material characterization and ultra-fast communication. Various technologies are working to increase the maximum oscillation frequency and power in the THz range. The highest oscillation frequency of 1.98 THz was achieved with the resonant tunneling diode (RTD) and it is the highest electronically generated frequency of oscillation. [1]. The RTD can achieve current densities up to 50 mA/µm² [2]. Losses in electronic devices such as series resistance or parasitic capacitance should be kept low since these limits the cut-off frequency. In this study, investigations of the electrical contacts concerning, the semiconductor materials and cleaning processes of the oxide layer before the metallization are carried out.

II. Experiments

For determining the specific contact and sheet resistances, TLM-structures with electrical contacts of differently sized gaps are fabricated. First, the mesa is formed using wet chemical etching with a phosphorous acid solution. Afterwards the metal contacts are applied in a lithography step.

First, various cleaning processes for removing the oxide layer before the deposition of the metals are investigated. The samples are cleaned with HCl: H_2O (1:4) for 20 sec, NH_3: H_2O (1:5) or NH_3: H_2O (1:5) for 30 sec. Afterward the deposition of the metal system Ti/Pt/Au (10/10/400) nm is carried out.

The next investigation aims to improve the semiconductor material system of the top-contact. A strained layer is used for the top-contact as reference sample, which is an n-doped InGaAs layer with 70% indium and a thickness of 8 nm. To develop the semiconductor material system of the top-contact, four layers are grown in which the indium content increases by 8% in each layer and the thickness of each is 5 nm. When the proportion of indium is increased, the electron mobility and the electron affinity increase. Then the barrier height drops. The last sample is produced from the previous layer structure. However, the growth temperature is reduced from 470 °C to 420 °C to increase the doping concentration.

In the third experiment an alloy contact system of Ge/Au is investigated at different alloy temperatures. Germanium penetrates the crystal through an alloying process and thus the doping concentration increases. The layer thicknesses of all samples are 30 nm germanium and 400 nm gold. The annealing temperature of the first sample is 250 °C with an increase of 50 °C for each sample, where time is constant.

The aim of the last investigation is to optimize the layer thickness of a non-allayoed metal system (Ti/Pt/Au). Titanium is used to improve the adhesion and Platinum to prevent diffusion of Gold into the semiconductor. Layer thicknesses of 3, 5 and 10 nm of Ti are deposited, while layer thicknesses of Pt are 10 and 20 nm. The layer thickness of gold remains constant at 400 nm.

III. Results

The cleaning process was carried out for metal contacts on lattice matched InGaAs to emulate the bottom contact and on a dummy sample with the top contact layer stack of 8 nm $In_{0.7}Ga_{0.3}As$. The bottom contact experiments have specific contact resistances between 12 and 22 Ohm*μm^2 and the top contact between 10 and 15 Ohm*μm^2. The deviation between all samples is low around 2 Ohm*μm^2. In order to notice the effect of the cleaning process, a sample should be produced without the cleaning process prior to metallization.

Evaluating the measurements in the second investigation shows a specific contact resistance of the top contact of the reference layers of 18.5 Ohm*μm^2. With an increase of the indium content, the specific contact resistance of the top contact drops by more than half. By increasing the doping concentration and the indium content as well, the specific contact resistance only decreases slightly by 20%. This can be attributed to the increased roughness due to the low growth temperature. The roughness measurements show an increase of Ra from 555.4 pm for the reference to 1304 pm for the experiment with a lower growth temperature.

Referring to the third investigation, it is expected from a reference that the optimized alloying temperature for germanium is between 350 °C and 400 °C [3]. Nevertheless, the measurements show that the specific contact resistance increases with increasing temperature. The specific contact resistance of this metal system is higher than that of the reference sample. The investigation shows that a damage to the metal layer at the top contact occurred when the temperature reached 350 °C or more. Gold does not adhere well on III-V semiconductors; therefore it may not hold up when the temperature rises. This led to a reduction in conductivity and thus an increase in the specific contact resistance. In order to avoid damage to gold, titanium can be used for adhesion.

Figure 1 shows the value of the specific sheet and contact resistance for different thicknesses of the metal system Ti/Pt/Au. It seems that the decrease in the specific contact resistance with a layer thickness of 10 nm of platinum. Therefore, the thickness of platinum should remain at 10 nm. There is a large standard deviation at 3 nm layer thickness of titanium, which is a sign of the inhomogeneous process. A layer thickness of the titanium between 5 and 10 nm is therefore recommended.

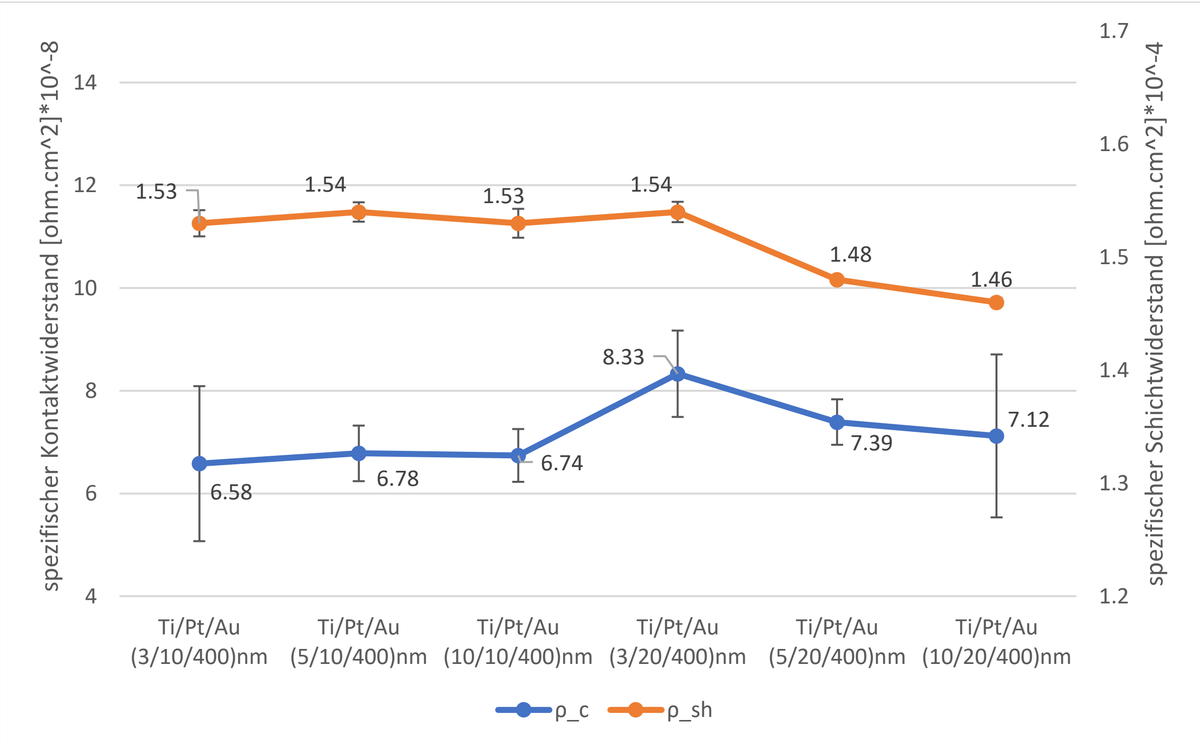

Figure 1: Specific contact and sheet resistance of the TOP contact from the metal system Ti / Pt / Au as a function of the layer thickness of the system

IV. Calculation of the influence of contact improvement

By substituting the specific sheet resistance, the specific contact resistance of the bottom- and top-contact and the dimensions of the RTD, the four components of the series resistance can be calculated. The series resistance of the reference system is 39.88 Ohm and of the developed system is 20.08 Ohm, where the top-contact area is 0.75*0.75 μm^2. Thus, the contact improvement of 49.64% can be proven. The diagram shows that the top-contact resistance contains the largest proportion.

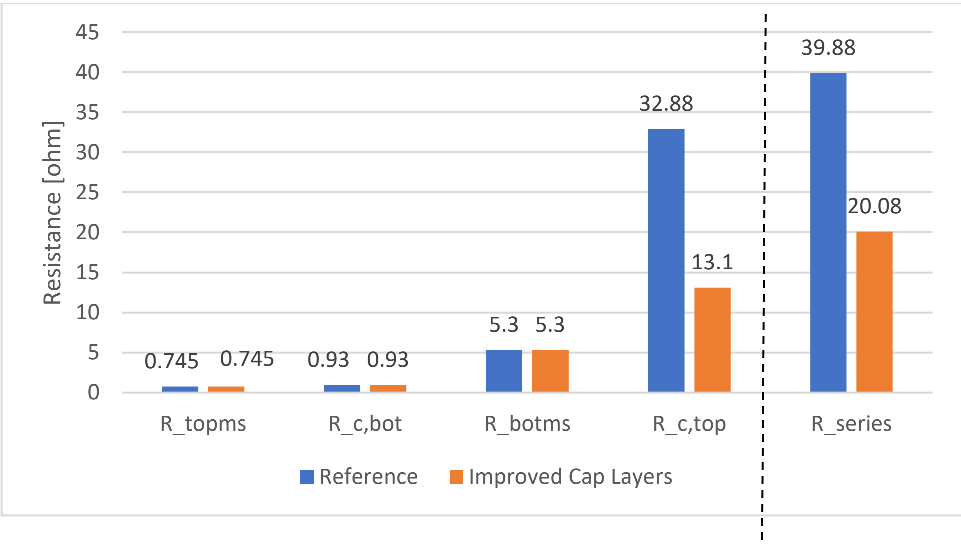

*Figure 2: Series resistance and its four component for the reference system of semiconductor and improved cap layers system for area of top-contact 0.75*0.75 μm^2*

The RTD can be described with a small-signal equivalent circuit consisting of a capacitance and a conductance are connected in parallel and an additional series resistor. The capacity of the RTD can be divided into intrinsic and geometric capacity. It is assumed that the intrinsic capacity is neglected and that the geometric capacity dominates. The geometric capacity for the intrinsic layer structure is calculated as a series connection of the individual layers, which is calculated to approximately 6.66 fF/μm^2. The conductance in the NDR range is derived from a large-signal model and it equals -12 mS / μm^2 [4].

S_{11} -parameter simulation is carried out based on these assumptions for different top-contact areas. S_{11}-parameter generally describes the reflection properties of an incident electromagnetic wave. Since this is a 1-port device, the S_{11}-parameter is initially sufficient to describe the RTD. An f_{max} can be defined as the intersection of the scattering parameters with the value 0 dB. This frequency thus describes the point from which there is no amplification of the signal. It is

Obvious that the smaller the top contact area, the larger the larger f_{max} . This is essentially due to the decreasing geometric capacity of the RTD.

In addition, the frequency f_{max} in GHz is plotted in the next diagram for the various top contact areas in μm^2.

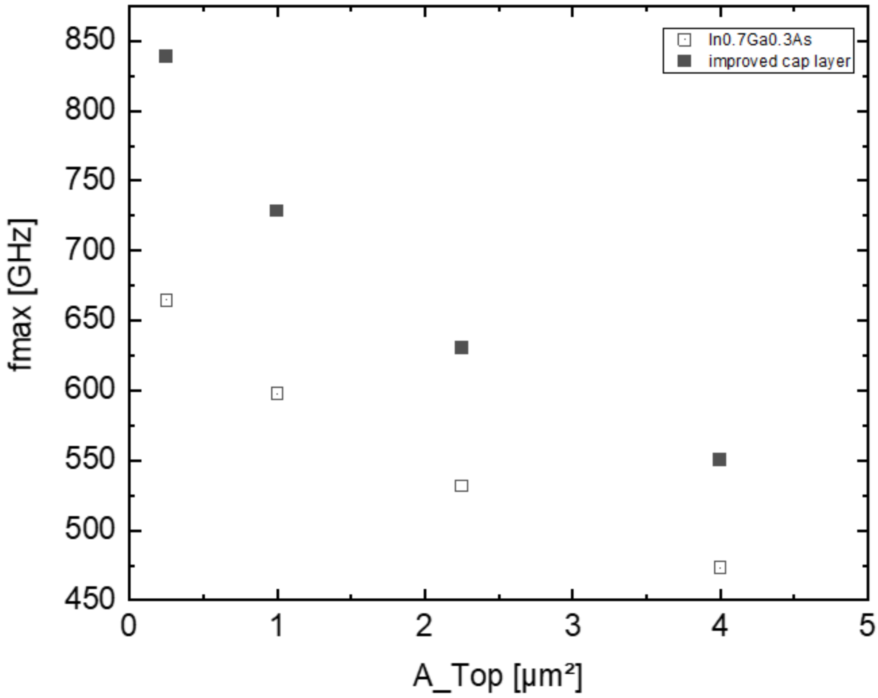

Figure 3: Frequency fmax as a function of the area of Top-contact

It shows an increase of fmax from 473.65 GHz to 664.8 GHz for the reference case. For the improved Cap layers an increase of f_{max} from 550.3 GHz to 839.22 GHz can be observed. This calculation shows a significant increase in fmax by around 20%.

V. Conclusion

In scope of this work, the developments of the electrical contacts in resonant tunneling diodes are presented. Optimizing the materials of the semiconductor system by increasing the proportion of indium using four Cap layers could reduce the series resistance of the half. Through S_{11} -parameter simulation with the calculated values, an increase of the frequency f_{max} by 20% is estimated.

VI. References

1 Ryunosuke Izumi; Safumi Suzuki; Masahiro Asada1.98 THz resonant-tunneling-diode oscillator with reduced conduction loss by thick antenna electrode*42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*Cancun2017

2 Takeru Maekawa, Hidetoshi Kanaya, Safumi Suzuki and Masahiro AsadaOscillation up to 1.92 THz in resonant tunnelingThe Japan Society of Applied Physics2016

3 L. Shen, V. Dolores-Calzadilla, C.W.H.A. Wullems, Y. Jiao, A. Millan-Mejia, A. Higuera-Rodriguez, D. Heiss, J.J.G.M. van der Tol, H.P.M.M. Ambrosius, G. Roelkens, and M.K. SmitLow-optical-loss, low-resistance Ag/Ge based ohmic contacts to n-type InP for membrane based waveguide devicesGhent2015

4 S. Clochiatti; K. Aikawa; K. Arzi; E. Mutlu; M. Suhara; N. Weimann; W. ProstLarge-Signal Modelling of sub-THz InP Triple-Barrier Resonant Tunneling DiodesIEEEEssen2020