DATERAC Executive Summary (2020-2024)

Introduction

The main objectives of the DATERAC project were the development of 2 innovative solutions for microwave reconfigurable circuits and antennas for future communication systems. The first solution consists in a direct integration of semi-conductor junctions in a substrate through localized doped areas associated with an electrical control. The second one is based on the optical control of Phase Change Materials (PCM), chalcogenide thin films in our case. Their association in a same device in order to increase its flexibility was also initially considered but was not implemented during this project because of some issues as explained below.

At the beginning of the project, the team was composed of 2 laboratories specialized in microwave and antennas (Lab-STICC in Brest and IETR in Rennes) and 1 additional partner (not funded by CominLabs), ISCR lab specialized in chalcogenide materials. During the project a 4th lab has integrated the team, the FOTON institute, for their skills and know-how in the fields of microelectronics and lasers.

Achievements and contributions

The works done during the project can be divided into two main categories: i) technological development and ii) topological one.

Technological developments:

The two reconfiguration solutions studied in this project had not the same maturity at the beginning of DATERAC. The solution based on the electrical control of integrated semi-conductor junctions had already been the subject of several works previously and it could be considered as mastered at the beginning of the project. No additional technological development, specific to this solution, was therefore envisaged at the start of the project. This reconfiguration solution being based on the use of high-resistivity silicon substrate (HR-Si), note that such a substrate was used for all the technological developments whatever the reconfiguration solution in order to make possible their association on a same structure.

The second solution investigated in DATERAC is based on chalcogenide thin films. Unlike the first solution, these were the first studies on such materials for microwave applications for the team and a lot of technological developments were needed and done during the project. For these first studies, $Ge_2Sb_2Te_5$ (GST) PCM was used because of its availability at ISCR with in-house glass targets and commercial polycrystalline one. It is deposited by sputtering technique in a plasma environment with a RF magnetron on 2-inch targets (see Fig. 1) and then etched by lift-off process.

Several characterizations were made on the first deposited layers: composition homogeneity on 2-inch wafers using EDS, electrical and optical characterizations, etc. As a first example, Fig.2 presents the resistivity characterizations on a 300 nm-thick GST layer with controlled sized in its two states. The PCM crystallization was obtained by a hot-plate annealing under neutral atmosphere at 400°C during 20 min. The obtained resistivity ratio is 1.17×10^5.

As the final objective is to be able to switch reciprocally from one state to the other using laser, some optical characterizations were also done. We demonstrated for instance that these deposited layers present an important absorption at 980 nm. This is a really interesting point because several semi-conductor lasers exist at this wavelength allowing their integration and their packaging in order to realize small reconfigurable microwave devices. Some fluency studies were also made with different spot shapes (circular/elliptical) and sizes. Indeed, the PCM areas envisaged in the final microwave devices have very different sizes (rectangle several hundreds micrometers wide and several millimeters long or very small squares). The spot shape could be used to optimize the switching process. These studies also helped us to determine the useful fluency domain (20-60 $mJ.cm^{-2}$) to achieve crystallization while avoiding deterioration of the PCM layers.

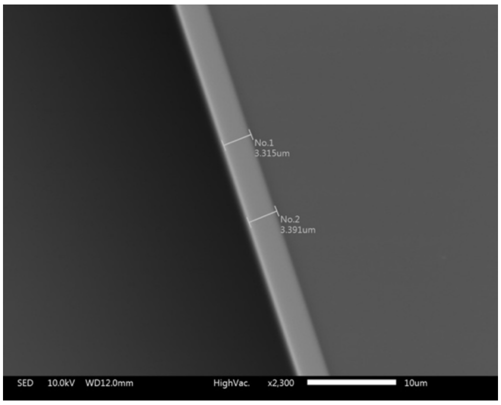

Fig. 1 – Example of GST deposition (Commercial target; deposition conditions: pressure 1.10^{-2} mbar, flow rate 73 sccm, power 20 W, deposition duration 2 h; obtained characteristics: deposition speed 28,3 $nm.min^{-1}$, thickness 3,4 µm, EDS composition determination Ge 22,5 %, Sb 26,6 %, Te 50,9 %)

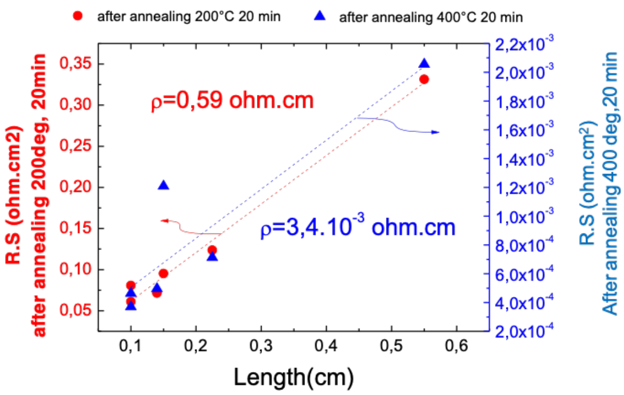

Fig.2 – Resistivity characterization after annealing.

Development of new reconfigurable device topologies:

In parallel of the technological aspects, we proposed new concepts of reconfigurable microwave filters and antennas. Our guideline here is to propose some topologies which take advantage of the reconfiguration technologies in order to optimize the inevitable compromise between reconfiguration capacities and performance.

Several solutions of reconfigurable filters were proposed. Two of them are associated with PCM and a third one with integrated semi-conductor junctions.

The first solution allows to increase significantly (from 10 to 30 %) the frequency ratio in the case of a central-frequency reconfigurable filter. This frequency ratio is usually limited by the inverters separating the resonators. These inverters are generally fixed or difficult to reconfigure with the conventional reconfiguration solutions (diodes, MEMS, etc.). As PCM can switch from a low-conductive state to a high-conductive one, they can be used smartly to modify easily the inverter behavior. An example on a DBR filter was developed here but this concept can be generalized to a lot of filter topologies.

The second reconfigurable filter topology allows to switch from a bandstop to a bandpass behavior and reciprocally by changing the PCM state. The bandstop filter consists in a simple set of quarter-wavelength open-ended stubs separated by quarter-wavelength lines. By connecting the open ends of two consecutive stubs, we can create square rings placed symmetrically. Such a structure has a bandpass behavior with two symmetric transmission zeros on each side of the pass band. A mathematical synthesis of this structure had been developed firstly for 3 stubs in the bandstop configuration of the filter and so two rings in its bandpass one. A generalization of this synthesis for any number of elements has been recently developed. Such syntheses facilitate the design of such filters for different specifications.

The third topology of reconfigurable filter uses integrated semi-conductor junctions to modify the behavior of a band-pass resonator. Several doped areas can be placed at different positions of the resonator allowing to change its resonance frequency but also its overall behavior and so its bandwidth and so on. Here again a complete mathematical synthesis has been developed.

Some reconfigurable antennas have also been designed. The main objective of these developments was to combine the 2 reconfiguration technologies. A first example is a simple patch antenna whose resonant frequency can be modified using integrated semi-conductor junctions while maintaining a good matching level thanks to the judicious introduction of PCM.

Assessments and encountered difficulties

We must recognize that the results obtained do not meet our expectations. We encountered some technological problems that have significantly hampered the progress of our work and the possibility of producing functional demonstrators. First, we were greatly impacted by the Covid-19 crisis including the closure of clean rooms and therefore the impossibility of producing circuits for a certain time. Moreover, the restart of the clean rooms was not without difficulties. For example, the first two sets of circuits with integrated semi-conductor junctions manufactured by our subcontractor (GREMAN Lab in Tours) were unusable because of a failed doping or metal lines peeling off. Our partner ISCR also had some difficulties after this crisis because of the delay in many projects and so the unavailability of the sputtering frame.

The main consequence is that the fabrication of a lot of demonstrators are now in progress. We hope that significant results will come in this first part of 2025. An update of this summary will be then done.

Nevertheless, all these difficulties and the few realizations we made gave us a lot of information for the continuation of this project. In fact, the main success of this DATERAC project is the building of a real team that will continue this work as part of an ANR project (ANR MACIEO, 2024-2028). This ANR project brings together the 4 laboratories involved in DATERAC (IETR, Lab-STICC, FOTON institute and ISCR). Two PhD students and a 2-years Post-Doctoral fellow have been hired and are working full time in this project. This ANR project is now really well launched because we learned a lot during the DATERAC project and therefore fixed most of the difficulties inherent in any technological development.

Production and PhD defense

Two PhD were half funded by the DATERAC project, the second half being funded by the Brittany region. One of the PhD students, Clément RAGUENES, defends his thesis on December 20, 2023. He now works as a research engineer for the Greenerwave company (Paris, France) in the field of microwave circuits and antennas. The second PhD student, Youcef AMARA, is currently writing his thesis. Nevertheless, as he works now for Intel Corporation (Antibes, France), this writing takes more time. The PhD defense is expected at the beginning of 2025.

- Clément RAGUENES: “Characterization and application of chalcogenide glasses to the reconfiguration of microwave circuits”, PhD in Electronics of the INSA of Rennes, December 20, 2023.
- Youcef AMARA: “Modelling and design of multi-reconfigurable systems based on dual Electrical and Optical Controls”, Defense expected at the beginning of 2025.

As explained before, a lot of demonstrators are now in progress. Therefore, the valuation of this project is currently limited. A document update will be made as new publications and communications associated with this project are accepted.

<u>*International conferences:*</u>

- C. Raguénes, E. Fourn, C. Quendo, R. Allanic, D. Le Berre, “Tunable feeding network for beam steering applications based on chalcogenide material”, 2023 IEEE Conference on Antenna Measurements and Applications (CAMA), Nov. 2023.
- C. Raguénes, Y. Amara, E. Fourn, D. Le Berre, C. Quendo, R. Allanic, C. Paranthoen, M. Perrin, V. Nazabal, A. Benardais, L. Calvez, R. Gillard, N. Martin, C. Levallois, “Multi-reconfiguration of microwave Antennas and Circuits with Independent Electrical and Optical controls”, 2024 European Microwave Week (EuMW), Workshop on Reconfigurable Devices Using New Materials and Technologies, Paris, Sept. 2024.

<u>*Invited conference:*</u>

- E. Fourn, “Towards multiple reconfigurations of microwave circuits and antennas by mixing substrate-integrated semi-conductor junctions and phase change materials”, Tunable Metasurface Workshop, Queen Mary University of London, Mar. 2024.

<u>*National conferences:*</u>

- C. Raguénes, E. Fourn, C. Quendo, R. Allanic, D. Le Berre, « Application de verre de chalcogénure à la reconfiguration de filtre DBR », 22èmes Journées Nationales Microondes, Limoges, Juin 2022.
- Y. Amara, R. Allanic, D. Le Berre,C. Quendo, E. Fourn, « Résonateur reconfigurable à base de lignes couplées à éléments d’accord intégrés sur substrat silicium », 22èmes Journées Nationales Microondes, Limoges, Juin 2022.
- C. Raguenes, E. Fourn, D. Le Berre, C. Quendo, R. Allanic, C. Paranthoen, M. Perrin, V. Nazabal, A. Benardais, L. Calvez, « Filtre reconfigurable passe-bande / coupe-bande à base de couches minces de chalcogénure », 23èmes Journées Nationales Microondes, Antibes Juan-Les-Pins, Juin 2024.