D1.3 - Intermediate exploitation report

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1 Potential impact

The global semiconductor memory market was anticipated to develop rapidly within the forecast period from 2015 to 2023. This was due to the increasing penetration of cell phones and advancement in technology, combined with the increasing adoption and popularity of smart devices. The emergence of Solid-State Drives (SSD) and mobile computing technology in the market was additionally foreseen to boost the development of the global semiconductor memory market in the future. Furthermore, surging demand in the electronic sector was also impacting the market growth positively. Evolution in the form of automation and digitalization in the entire electronics sector, along with the use of memory-based elements in technologically advanced products in several industries, such as automotive, IT and telecom, and consumer electronics, etc. are escalating the global semiconductor memory market. The expanding usage of semiconductor parts in the electronics and automotive systems, for example, NAND Flash, DRAM, and others, are the key generators for the demand regarding the integrated gadgets and chips. The automotive frameworks, for example, automated safety, luxury, driving and control frameworks that consolidate various storage solutions, will give expanded speed and network in self-ruling and electric vehicles.

The world market for non-volatile memory was thus projected to gain momentum in its growth, owing to the increasing demand in the consumer electronics and automotive industries.

The mushrooming coronavirus outbreak in the central Chinese city of Wuhan prompted the World Health Organization (WHO) to declare a global health emergency in late January. The coronavirus outbreak is not just a massive health crisis; it is an economic one as well.

The automotive industry has seen the impact of the coronavirus crisis evolve from a supply shock to a global demand shock. The forecast is that automotive sales most likely will decrease by 14-22% among the China, US and European markets in 2020. In fact, the SARS2-COVID-19 pandemic has had a severe impact on the globally integrated automotive industry, including a disruption in Chinese parts exports, large scale manufacturing interruptions across Europe, and delays in assembly plants in the United States. Furthermore, global passenger vehicle sales declined by nearly 7% in July 2020, despite regions showing varied signs of slight recovery from SARS2-COVID-19 induced lockdowns.

While most regions are certainly seeing signs of improvement, it remains difficult to ascertain the actual market situation. As a result, several economy analysts continue to hold onto their 2020 annual outlook of nearly 20% decline over last year.

If the pandemic is not contained to a large extent, the drop in consumer demands and industrial production could potentially push the global economy into a recession in 2020/2021.

Such a global economic scenario should be taken into account in considering the short- and long-term period capability of impact of BeforeHand to innovation.

2 Universities and Research Centers

For the participating University and Research Centres main impact of project results took the form of dissemination through publications and participation in conferences. Of course, care has been taken to avoid disclosing critical information, but it is expected, through the highly innovative content of the research, that ample material for publications will be available.
Dissemination and outreach actions have been reported in D1.6. Information on dissemination included:

- result publication in refereed journals and conference proceedings
- participation in workshops and conferences.

The publishable results have been also put on the BeforeHand website.
In the following, some more details are provided on the impact for each partner.

2.1 CNR

During the BeforeHand project CNR on itself and in cooperation with some of the consortium partners produced a large number of results. Some of them are of technical nature, especially those dealing with sample preparation and characterization. Most research results have already been exploited in terms of talks and papers; in fact, some have been presented to the research community and most of them have also been published, already. Some results, however, are still in the form of reports, but will be published in a more widely recognized form of publication.
A further contribution of CNR to the project is the investigation of an alternative method for fabricating a regular array of PCM nanowires in anodic aluminum oxide nanoporous membranes, as needed for high-density memory elements. Today, the fabrication of these devices is mainly based on a top-down approach by etching the planar structures to define the wished size. The performance of all devices fabricated in this way is, in principle, limited by defects generated by

the required processing steps. Furthermore, for the realization of economically viable solutions, not only as PCM, but also to different kinds of devices, including thermoelectrics, spintronic and neuromorphic applications, the monolithic integration of nanowire devices with the selector is of particular interest.

The technical knowledge obtained by CNR in fabricating different electrical testing vehicles, as well as the expertise gained in the electrical testing of non-volatile memories, makes CNR an attractive partner for future collaborations or projects for both academic and non-academic institutions. Moreover, the investigation on the physical mechanisms producing the degradation of the device performance, in terms of reliability, in the case of Ge rich alloys or multilayers, can be exploited to answer fundamental questions and the results can be used for a better tailoring on phase change materials, also for different applications.

The physical properties of solids strongly rely on their periodicity. Here, multilayer structures offer a unique pathway to tailor such properties as the size of the unit cell can be adjusted. This has been already exploited in photonics, thermoelectrics and magnetic materials, to name a few among others. The multilayers thoroughly investigated within the framework of the BeforeHand project are therefore potentially interesting also for the other applications.

Thermoelectric materials are characterized by an efficient conversion of a heat gradient into accessible electrical power. This is governed by the thermoelectric figure of merit. Multilayer structures are one of the novel concepts in the field of thermoelectrics. They are of particular interest, due to their strikingly reduced thermal conductivity, as compared to their constituent counterparts. The insights on the highly textured growth obtained within the framework of the BeforeHand project might thus be exploited in future research also on thermoelectric devices.

Additionally, 2D bonded higher-order chalcogenides, such as Bi_2Te_3, Sb_2Se_3 and Sb_2Te_3, are proven to be 3D topological insulators. In the meantime, also fingerprints of topological insulating states are found in layered PCM GST alloys. The experience gained in this project on the growth of Sb_2Te_3 may therefore be exploited to contribute to research activities in this approaching field.

The gain in expertise on multilayers that can be considered as layered Van der Waals (vdW) materials, i.e. covalently bonded in only two dimensions (2D), will be also exploited to answer fundamental questions. Working further on the interfaces of 2D bonded materials we might discover the way to vdW heterostructures to drive their functional properties. For instance, one could question whether the enhanced performances stem from the periodicity and precise thickness of the sublayers, like in the case of GaAs-based heterostructures for quantum cascade laser applications, for example, or whether they are more related to the vdW interfaces.

Finally, the project concurred to the formation of young researchers in CNR, through the positions assigned (Giorgia, Greco, Francesco De Nicola, Marzia Buscema, Adriano Diaz Fattorini, Arun

Kumar, Iñaki Lopez Garcia). Some of these young researchers are expected to continue their collaboration with CNR in the future.

2.2 PDI

The unique control of the growth parameters allowed by molecular beam epitaxy (MBE) is fundamental to fabricate material of extremely high quality compared to other techniques. Thus, it enables to study structural properties and in general physical phenomena with much better accuracy. As described in detail in D1.1, PDI has a large expertise in the epitaxy and characterization of Ge-Sb-Te materials and heterostructures. While our research has been mainly devoted to phase-change properties, we have been also studying topological, ferroelectric and most recently thermoelectric properties. The playground on which we acted comprises Sb_2Te_3, GeTe, GST with composition between 124 and 326, and $Sb_{2+x}Te_3$, both as thin films and as constituting layers in multilayer and superlattice structures.

The materials and device applications targeted within BeforeHand project constitute a challenging, but at the same time, inspiring opportunity for widening the activity of PDI, both on material fabrication and characterization (in house and in collaboration). Indeed, epitaxial Ge-rich GST alloys were attempted in PDI for the first time in the framework of the project. (i) Starting from the optimized growth conditions of GST225, we obtained an unprecedented control of the alloy composition in a wide range, even though these are along the pseudobinary line. Such phases are ready to be used as building blocks in more complex heterostructures (two exemplary bilayer stacks were shown). This research is carried out leveraging greatly on the strong collaboration existing with other units in the consortium, and will undoubtedly lead to several novel results and publications. PDI is at present leading the preparation of two publications on structural and Raman properties of these alloys. (ii) Complementary to the previous study, we explored GST alloys very close to the binary compound GeTe (Sb-poor). In collaboration with the ESTEEM3 consortium, we applied for and obtained access to the high-resolution STEM facilities in Catania (project EPIGEO, ID:99, analysis ongoing). These experiments may have implications which exceed PCM applications, opening the way for further investigation and projects beyond BeforeHand.

As a follow up of the activity on epitaxial Ge-rich GST alloys, we realized Sb_2Te_3/Ge heterostructures, aiming to mitigate the formation of epitaxial GST films along the pseudobinary line. Strikingly, we achieved epitaxial quality films and spotted the presence of superstructures, as intended. The samples are currently being further characterized within the consortium. We expect

this activity to lead to secure scientific outcomes, which may be of interest to the industrial partner and a broad scientific community.
Moreover, we initiated in collaboration with CNR-IMM in Catania a systematic activity on the study of crystallization of amorphous GST alloys and heterostructures, which is a further element of novelty in PDI portfolio.
A part of the research results described in the previous paragraphs has been obtained in the last 12 months. Since this period sadly coincides with the outbreak of the Covid-19 pandemic, a proper exploitation in terms of dissemination to the research community (e.g. at conferences) was largely not possible. On the other hand, several papers are in preparation and some will be published in the course of next year.
Finally, the project is concurring to the development of the career of Dr. S. Cecchi (responsible of PDI unit since 2020), in particular providing the formation on management skills. This is particularly relevant for future grant applications. Also, the training of a technical employee which has been started in the last six months is valuable for PDI future activities.

2.3 LETI

During the first year of the project, LETI contributed to the development of the single-cell vehicle. This integration vehicle was not available at LETI and had to be developed. In doing so LETI has produced with the consortium a versatile test vehicle that can be used to characterize not only PCM materials in BeforeHand, but will be also of use for the characterization of other types of chalcogenide materials in the near future. This vehicle can give valuable insight on materials properties without having to engage very lengthy (several months) process integration to characterize materials. This vehicle is therefore very interesting for multiple material screening and will be used from now on for PCM and other materials.
Within BeforeHand LETI is able to gain valuable expertise in the growth and structural characterization of multilayers.
The multilayer development using PVD tools at LETI helped us to assess the capability of our state of the art 200mm PVD tools to deposit amorphous multi-layered structures with nm control of individual layers. This processing capability is crucial for the project BeforeHand and beyond for thin chalcogenide deposition process control and repeatability.
The sample exchanges and technical collaborations with CNR and CNRS helped us to progress in the understanding of the physical phenomenon behind the structural evolution of those multilayers in temperature. In particular complementary structural characterization techniques such as Raman spectroscopy, in situ X-Ray diffraction, TEM analysis, Modulated Photothermal

radiometry have been accessible through BeforeHand partners and proven to be very useful to select the best materials to integrate.

Through those technical exchanges, we were able to build strong collaborations with internationally recognized experts in the field. As a consequence, we have co-authored several articles and communications and have strengthened our international visibility in the emerging non-volatile memory community. This last point is important, since it will help us to be more attractive as a research organization and eventually will help us to build more academic collaborations through collaborative projects but also attract potential industrial partners.

2.4 URTOV

The main target of BeforeHand project is the realization of chalcogenide heterostructures, aiming to provide a processing/storage, all-in-one device, to be embedded in automotive IoT smart devices. Furthermore, such heterostructures should exhibit improved properties in terms of, *e.g.*, latency and data retention. In this regard, as stated above, multilayer structures offer a unique pathway to tailor such properties as the size of the unit cell can be adjusted. Multilayers and heterostructures have been exploited in many fields of semiconductor electronics, making the research carried out within the BeforeHand consortium potentially impacting a large number of applications other than the ones focused on the BeforeHand project.

Within the BeforeHand project, and in collaboration with some of the consortium partners, URTOV unit is contributing with both growth and spectroscopic studies. Some of the results were included in the deliverables released for WPs 2 and 3 and others will be included in the next deliverables of WP 4. It is important to note, that an important contribution of URTOV unit comes from the photoemission (XPS and UPS) studies performed *in situ* on PVD samples. Several alloys were grown and studied *in situ* and compared with the results obtained on MBE samples grown by PDI unit and studied *ex situ*. Recently, several heterostructures were also grown by PVD. The evolution of their electronic properties was studied *in situ* during the formation of the interface between the different layers in order to understand whether a sharp or intermixed interface is formed. The interfaces are expected to have a fundamental role in the switching properties of the multilayers and the understanding of their switching mechanism is a milestone of WP4. These results will be the main topic of deliverable 4.3 that will be developed in collaboration with UMB and PDI units.

PCM chalcogenide alloys containing Sb_2Te_3 behave as a 2D material due to the presence of vdW gaps introduced by Sb_2Te_3 into the crystal lattice. Sb_2Te_3 is a topological insulator and non-trivial surface states have also been found in these materials. The heterostructures investigated in BeforHand can be also considered layered materials, therefore the results obtained in the study of

interfaces formation can also impact the field of 2D materials, vdW heterostructures, as well as the comprehension of some of their exotic functional properties. Some preliminary results were presented at the recent MRS2020 Virtual conference held in November-December 2020, and a publication is in preparation.
Finally, URTOV is a University unit and the formation of students is one of its missions. Until now, BeforeHand research was the topic of one master thesis (Adriano Diaz Fattorini) and one Bachelor thesis (Christian Petrucci) and another Bachelor thesis is currently ongoing (Davide Rinaldi). BeforeHand is also contributing to the formation of a researcher through a post-doc position assigned to Caroline Chèze.

2.5 UGRO

The BeforeHand project allows UGRO to further develop its expertise along two major lines.
The first one is concerned with pulsed laser deposition (PLD) of phase-change thin films, heterostructures and multilayers. The most widely employed technique worldwide to grow PCMs is sputtering, but PLD is growing in popularity. The advantage of PLD is that it has more variables for controlling the growth and it is relatively easy to switch between targets with rather different compositions. Therefore PLD is particularly suitable for heterostructures, multilayers and even in specific cases superlattices. Still, it turns out that PLD is rather sensitive towards the quality of the target. Before the BeforeHand project we always purchased commercial targets. With the BeforeHand project we started to produce our own targets, which gives more flexibility to tune the composition and morphology (grain size, porosity) of the targets. This turned out to have large effects on the quality of the films we could produce. Moreover, when working on a new PCM, GaSb, using a fully dense target, we found out that it is very important to apply 180 degrees target rotation after a limited (say 1000) pulses. In the end, BeforeHand has contributed strongly to improve our expertise on PLD (of Sb and Te based materials) which will be summarized in papers and will be exploited in future research projects. This not only applies to the growth of PCMs, but also the growth of heterostructures and multilayers for optoelectronic (metamaterials) and thermoelectric applications.
The second line is concerned with advanced scanning transmission electron microscopy. With the start of BeforeHand also a new state-of-the-art scanning transmission electron microscope (double aberration-corrected and monochromated) became operational in the UGRO group. One of its innovative features is that it contains the largest EDX detectors available worldwide and therefore can very efficiently capture X-rays when a very small (e.g. 2 Angstrom) electron beam probes a very thin TEM sample. We have applied this technique to analyse the composition and

stacking of the different nanoscale sublayers in heterostructures and are currently using it to measure the intermixing at Sb_2Te_3-GaSb interfaces. When these results will be published, along with other breakthrough research that is performed (e.g. imaging for the first time hydrogen atoms), this will improve our visibility and establish us as a leading STEM group in the world.
The increased expertise in each line makes the UGRO group more attractive for future collaborations, both with academia and with industry, i.e. when PLD or HR-STEM is required.

Young researchers have been trained by BeforeHand workers, i.e. bachelor student (Arsen Tskhay) and master student (Julien van Ree), where the latter is now starting as a PhD student in the UGRO group.

2.6 UMB

Partner UMB has a strong expertise in the atomistic simulation of phase change materials that has been exploited during the BeforeHand project to aid the interpretation of the experimental results gained by the other partners and also to aid the selection of the most promising materials. The results of the research have been exploited in terms of talks at international conferences (three) and papers on peer-reviewed journals, already published (three), submitted (two), or in preparation (two). Some of these papers are in collaboration with the experimental partners when UMB provided a theoretical guide to interpret the experimental results. Others are authored just by UMB when theoretical predictions are made on the properties of materials waiting for experimental confirmation.
The activity within the BeforeHand project provides the opportunity for the UMB group to gain additional expertise on particular simulation techniques such as the genetic algorithm used for the prediction of the crystalline structure of GaSbTe alloy that will be further exploited for other materials as well. Moreover, in early 2020, the UMB group started the activity on the generation of a neural network potential for Ge-rich GST alloys that, once available, will pave the way for realistic large scale simulations of the transformation processes of GST alloys of interest for embedded memories within BeforeHand, but also for storage class memories and neuromorphic computing with a potential impact on other projects and future collaborations with industries. Finally, the project concurred to the formation of young researchers, O. A. El Kheir and D. Baratella first as undergraduate students and then PhD students, C. Ribaldone as undergraduate student and D. Dragoni as Postdoc.

2.7 CNRS

The I2M laboratory develops experimental and theoretical expertise in the thermal properties of materials over a temperature range from 3K to 1500K. The observation scales are of the order of hundred nanometers, from near-field thermal microscopy, to larger scales by the use of appropriate photothermal experiments. During the BeforeHand project, the Ge-rich GST (GST = $Ge_2Sb_2Te_5$) alloys as well as the Ge-rich GST / GST superlattices were the subject of several experimental campaigns using the MPTR (Modulated PhotoThermal Radiometry) and PPTR (Pulse periodic PhotoThermal Radiometry) methods. The thermal conductivity measurements of these thin films were carried out at ambient to 450°C. The thermal resistance values at the interfaces have also been reported over the same temperature range. These measurements demonstrated the glass transitions as well as the evolution of the crystalline phases as a function of the temperature. Those results were compared with the electrical resistivity measurements carried out by LETI over the same temperature range, which also leads to isolating the electronic contribution on thermal conductivity. All the samples used for this experimental characterization were carried out at LETI. The thin layers are deposited in several thicknesses and covered by an optical-to-thermal transducer. For information, the samples characterized at I2M are then returned to LETI which performs XRD and Raman characterization in order to verify the integrity of the layers following the thermal loading undergone. the MPTR and PPTR measurements as well as the extraction of the heat transport properties were carried out by Clément Chassain, PhD. A technician (Yannick Bafanga) was made available by the Epsilon Ing. company for the realization of the high.temperature furnace on the PPTR device. Two Master internships (Mélina Panier and Hughes Giraud) contributed to the definition and creation of the interface for temperature control and the high-frequency amplifier on this device.

In parallel to these experimental activities, models of the evolution of thermal conductivity have been developed in order to highlight the main phenomena responsible for the variation of the crystalline phase with temperature. For this, two approaches have been implemented. The first is based on the approximation model of the phonon relaxation time within the Boltzmann transport equation. This classical analytical approach makes it possible to represent the relative contributions of each scattering mode, Umklapp scattering and defects, in a fast and identifiable way from the experimental values. The second approach, of the ab-initio type, is carried out jointly with the UMB, which has the best expertise in this field. This theoretical work is led by Kanka Gosh, a post-doctoral fellow hired within the framework of BeforeHand and who works in close collaboration with Marco Bernasconi of the UMB.

A publication on theoretical aspects has been accepted in Phys. Rev. B. Two other publications on experimental activities are being evaluated in Appl. J. Phys. Two presentations at the EMRS and IHTC conferences are scheduled for August 2021.

3 Industrial exploitation

3.1 STM

STMicroelectronics is focused and holds a solid position in the "Automotive", "Industrial", "Personal Electronics", "Communication Equipment, Computers and Peripherals" end markets.

Market trends are driven by automation, requiring greater energy efficiency, IoT nodes capable of processing a large amount of data, in an extremely fragmented industrial market, with many different applications.

ST's needs are to maintain leadership in integrated computing, and enabling AI, with a low power solution like with PCM, will become a key differentiator.

ST's strategy is to strengthen its leadership position in integrated processing with the following key enablers:

- increasing the usage of STM32 microprocessors for the industrial market
- proliferation of the STM32 microcontroller SoC that integrates wireless connectivity and advanced security features
- inclusion of Artificial Intelligence in all segments (via SW solutions and HW accelerators)
- establishing a leadership position for advanced security solutions.

The exploitation of MCU-based solutions coupled with an eNVM is increasing very rapidly both for "General and Safe Use of MCU market" (where ST ranked #1) as well as for "global MCU market" (where ST ranked #4) [Source IHS Markit].

For this reason, looking for an emerging-NVM solution capable to guarantee automotive-grade (either for operating range and/or for soldering reflow compliance), single bit alterability, low power consumption, extended endurance is considered crucial.

In this framework, the synergy with the BeforeHand research activity is of key relevance:

- tuning of Ge-rich GST alloy stoichiometry as well as the identification of an alternative promising chalcogenide compound satisfying automotive-grade specifications will allow ST to widen the offer to meet customer requirements.

- the scaling activity carried out both on the integration of next-gen device like Multi-Layer Heterostructures (ML) and the integration feasibility of core-shell Nanowires (NW) based on Ge-rich compounds will further support ST in paving the way to boost programming performances (i.e. programming current reduction) to enable chip design with memory array area reduction and improved reliability. These features are particularly appealing, for instance, in the fast-growing mobile-wearable segment.

In the mid-term, ST will gather the benefits from the BeforeHand research, transferring all the know-how that will be acquired about deposition techniques of the chalcogenide layers, etching and cleaning recipes and all the tricks from an integration viewpoint of Multi-Layers Heterostructures.

For the same reason, the project efforts put on the core-shell Nanowires integration and possible solutions for array definition have the same relevance even though they can be considered, up to nowadays, a long-term solution.

A tight collaboration between Research Centers focused on epitaxial growth on small samples and LETI, with its advanced pilot lines, will be fundamental for the transition phase, porting the promising solutions inside an industrial environment.

As a direct consequence, ST is strongly engaged to carefully monitor all research outcomes to file patent requests, in tight collaboration with the consortium partners, to protect sensitive IP developed.

In this way, ST will strengthen its NVM technology solutions to be able to keep on playing a major role in the main categories where memory is already required (see table 1 below) and to be ready to serve new business opportunities with AI edge and In-Memory-Computing solutions.

Application	MCU	SIM Smart cards	IoT	Auto
Operation Temperature	-40C ~ 125C	-40C ~ 85C	-40C ~ 125C	-40C ~ 165C
Bus Width	x32 / x64	x32 / x38	x32	x144
Standby Current	<1µA @ 25C	<1µA @ 25C	<1µA @ 25C	<1µA @ 25C
Read Current	<5mA / 33MHz	<5mA / 33MHz	<2 mA / 40MHz	<40mA / 200MHz
Access Time	<20ns	<40ns	<25ns	<15ns
Endurance	10K	500K	100K	500K
Data Retention	10yrs	10yrs	10yrs	10yrs
Soldering (a few min. @ 260C)	Yes	Yes	Yes	Yes

Table1: Main product specifications for most relevant eNVM applications

ST pushes the research on PCM scaled solutions as they are considered a key success factor in the automotive MCU arena and will be essential for competitiveness in this market, where significant risks related to the combination of new circuit design and new technology solutions will be involved. In Figure 1 we show the different possible usage of MCUs in the automotive application field.

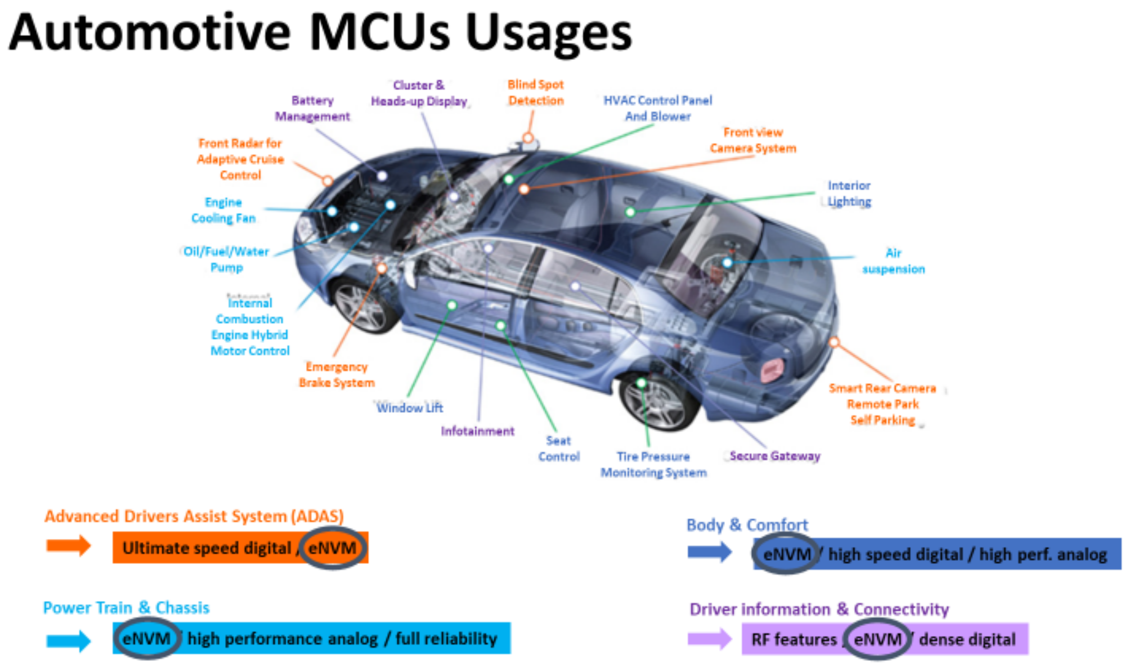

Figure 1: Automotive MCUs usages.

As an example, on advanced CMOS logic technology, from the 28nm node, the CMOS transistor structure has radically changed from silicon dioxide with polysilicon gate to CMOS structure with high-K dielectric and metal gate.

Within this disruptive change, the so-called emerging NVM (like PCM) needs to be ready for next-generation MCU from a process integration viewpoint.

In table 2 shown below, it is reported a benchmark of an ST automotive-grade chip (2nd column) with the most advanced chips of competing technologies, at the time this chip was presented.

It can be noticed that only the ePCM chip covers the automotive temperature range, with the smallest cell (normalized to the technology node feature).

This 28nm FDSOI technology places ePCM at the forefront of the eNVM competition, in the challenging transformation from conventional logic CMOS (SiO_2 gate oxide technology) to High-K metal gate and FinFET.

	[1] ISSCC2015		This work		[2] ISSCC2018	[3] ISSCC2018
	Code	Data	Code	Data		
Technology	28nm SG-MONOS		28nm FD-SOI PCM		40nm RRAM	28nm STT-MRAM
Integration	FEOL		BEOL		BEOL	BEOL
Memory cell size	$67F^2$		$40F^2$		$53F^2$	$75F^2$
Memory size	2MBx2	64KB	6MB	256KB	11Mbit	1Mb
Power supply	1.1V+/-0.1V, 2.7..5.5V		0.85V/1.1V, 2.7V..5.5V		1.1V	1.2V/1.8V
Operating Temp.	-40°C to 170°C		-40°C to 165°C		-40°C to 125°C	25°C to 120°C
Read I/O (#bits)	(128+10)x2	32 + 7	(128+17)x2	128+17	NA	16
Random Access Time	5ns	100ns	<9ns full V/ T° range		9ns @ 1.1V, 25°C	6.8ns @0.85V, 25°C
Program Speed	2.0MB/s	150us/4B	0.61MB/s	30us/32b	NA	
Erase Speed	0.91MB/s	1.5ms/64B	No erase	No erase	No erase	No erase
Modification speed	0.63MB/s	1.65ms/4B	0.83MB/s	30us/32b	NA	
Write endurance	10k cycles	>1MB cycles	1k cycles	Tgt: 100k cycles	1k cycles	
Read window @ 10^{-5} BER			10μA @ 1…10k cycles, 25°C		22μA* @ 1k cycles, 25°C	
Max Memory Capacity	32MB	512K	32MB	512KB	NA	NA
Bit/Byte Alterability	N		Y		Y	Y

Table2: Comparison of the main characteristics of the microcontroller made in 28nm ePCM FD-SOI technology and the state-of-the-art at that time (Disegni, et al. VLSI2019)

Embedded PCM, from Ge-rich GST bulk alloys to Multi-Layer Heterostructures and to Ge-rich core-shell Nanowires, may become the mainstream eNVM technology for 28nm node and beyond, at least for automotive-grade applications.