F-RAM in xEV automotive applications

Harsha Medu – Principal Engineer Applications
Karthik Rangarajan – Sr Manager, Product Marketing
Mathew Anil – Marketing Director, Vehicle Motion

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Introduction

With the increased push to reduce the use of fossil fuels and their associated emissions for a sustainable future, Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) or xEVs will experience unprecedented acceptance and growth over the next few years. With increased electrification, more data becomes available to be sensed and measured which increases the need for data-logging. Although there are traditional non-volatile memory technologies like EEPROM and Flash for data-logging, F-RAM (Ferroelectric Random Access Memory, also F-RAM or FeRAM) with its unique technology benefits of zero-delay writes, low switching energy, virtually infinite endurance, and long data retention, is positioned to be the data-logging memory technology of choice for battery management systems, inverters and more in xEVs. This whitepaper will explore the key automotive xEV applications and their requirements, details on various data-logging memory technologies and specific F-RAM solutions to address the needs of automotive applications.

Memory technology background

Non-Volatile Memory (NVM) is required for data-logging in many automotive applications and any system that needs to store frequently updated data. Incumbent memories in these systems are usually floating gate memories like EEPROMs and Flash, which suffer from slower writes and sub-optimal write endurance. Consequently, there is a constant risk of losing out on mission-critical data and designing with complex software overheads to manage the limited endurance. With F-RAM, a vehicle's systems can continuously store data at full bus speed without the need for additional memory capacity and overhead to manage the memories' endurance. Since F-RAM is instantly non-volatile, it requires no additional soak-time to commit the data to non-volatile storage. In addition, F-RAM has a write endurance of 10^{14} cycles, where most EEPROMs and Flash have less than 1 million (10^{6}). Based on this capability, market research firm Lucintel expects the global F-RAM market will grow with a Compound Annual Growth Rate (CAGR) of 10% to 12% from 2021 to 2026 with automotive being one of the major drivers for this growing demand [1].

Automotive xEV design challenges

Currently, there are a broad range of automotive F-RAM applications including event data recorders, tire pressure monitoring, navigation, and engine control. These applications take advantage of F-RAM's ability to store data instantly during critical events, excellent durability in terms of data retention and endurance, low power consumption, and more. Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs), or xEVs provide new possibilities. An xEV mainly includes a Battery Management System (BMS), an on-board charger, and a main inverter (INV) as shown in Figure 1. F-RAM performs critical functions in BMS and INV designs.

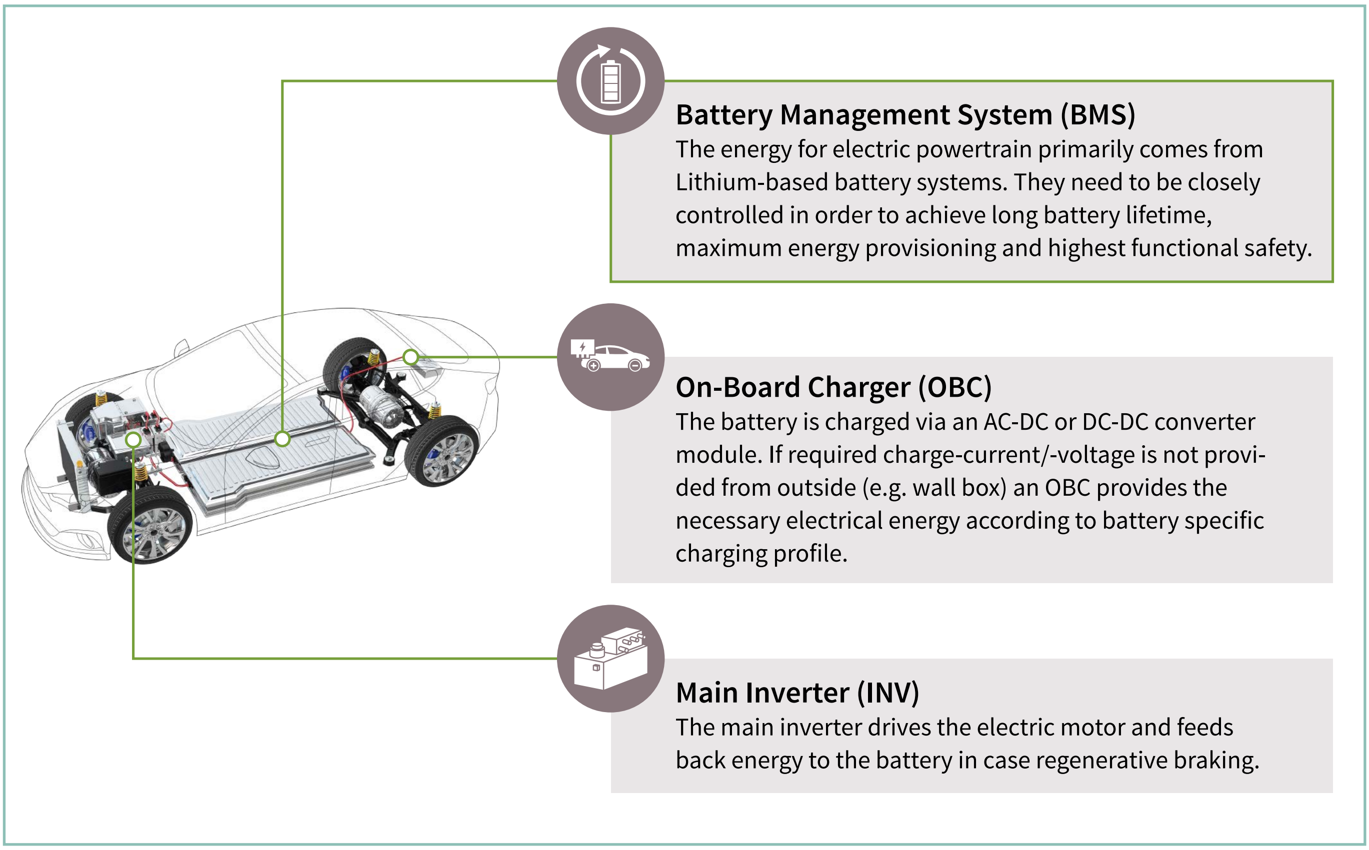

Figure 1: In xEVs, the battery management system and main inverter provide significant design-in opportunities for system designers to take advantage of F-RAM's unique and outstanding capabilities.

Design challenges in xEV battery management

The key functions of the battery management system in xEVs include protecting each battery cell from damage, prolonging the life of each cell, and providing real-time energy distribution to the vehicle. Figure 2 details the functions that the BMS must perform towards achieving these objectives.

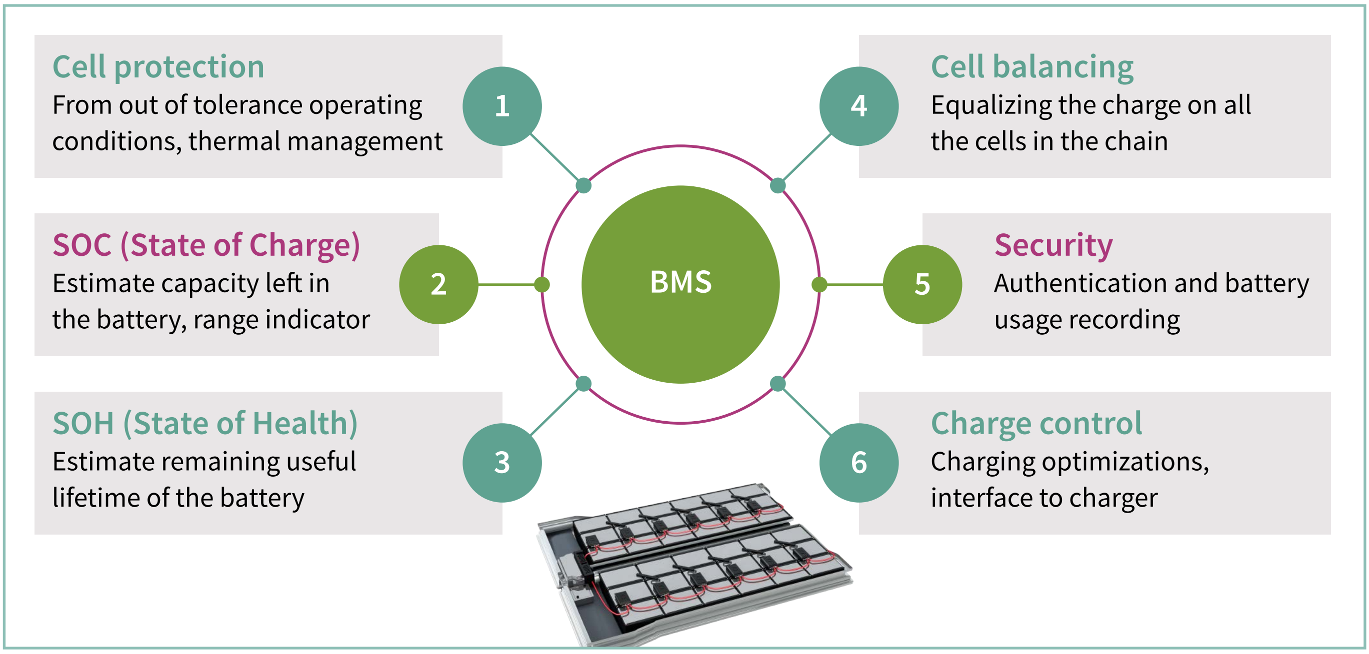

Figure 2: Key functions of a battery management system.

The battery management system needs to log the vital parameters like voltage, current, temperature, and others to derive information on actual cell capacity, State of Charge (SOC), State of Health (SOH), power consumption (charge/discharge), remaining operating time of cell, etc. These parameters are logged at approximately 1 sample/second in a non-volatile memory (see Figure 3).

As an estimated parameter, state of charge is important since it prevents the cell from overcharge and over discharge. Since SOC is calculated based on the previous value, this parameter is typically stored in non-volatile memory. In contrast, state of health measures and stores the health of the battery cell. The history of the battery, stored in memory starting from its installation, is important in determining the SOH.

Cell capacity is another essential BMS parameter. Cell capacity and SOC together determine if a cell is over charging or over discharged. Cell capacity is also stored in non-volatile memory and updated over time. Similarly, the memory is also used to store the other statistic and diagnostic information which help in predictive maintenance of the battery system.

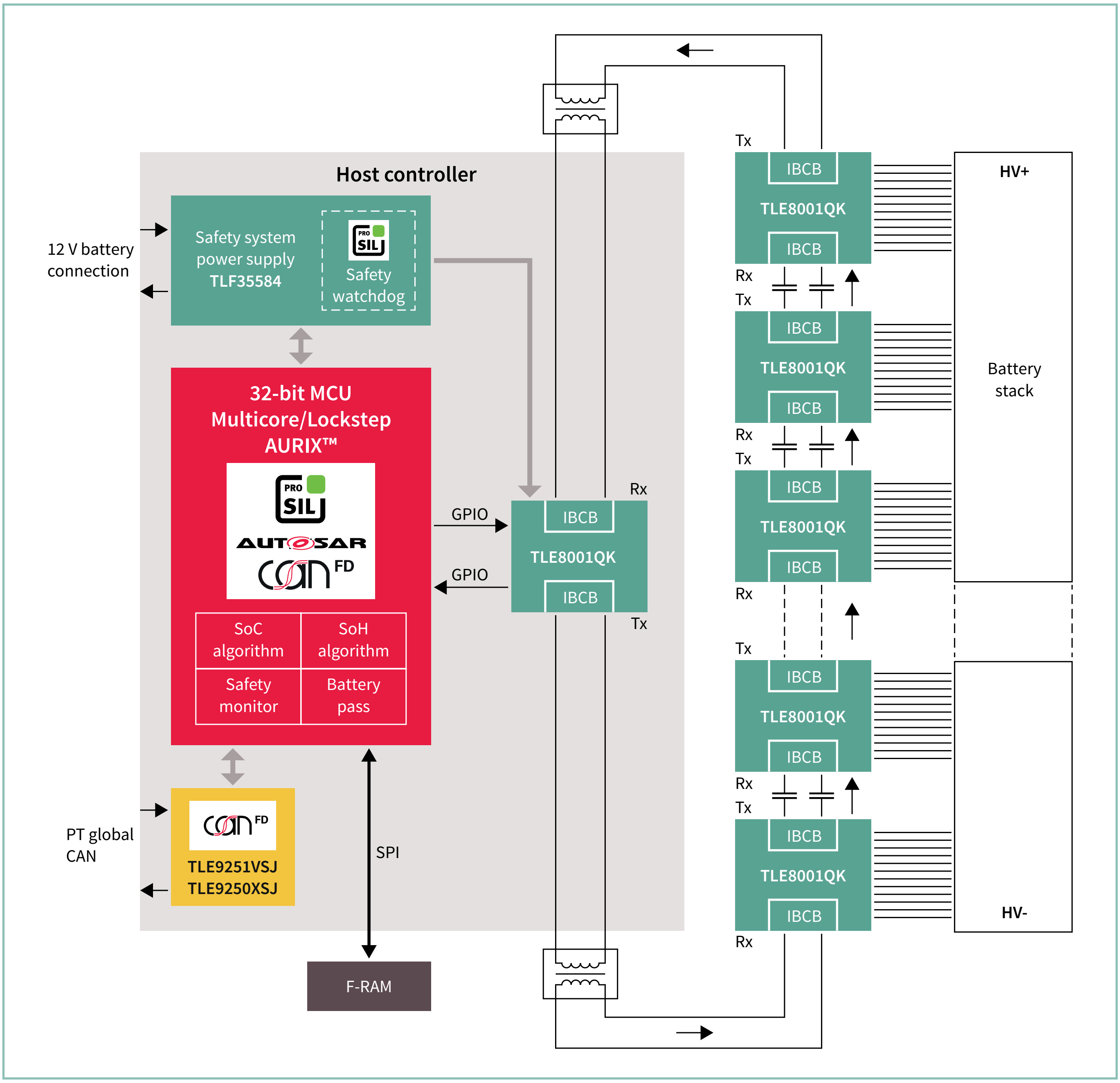

Figure 3: F-RAM usage in the battery management system.

Design challenges in xEV inverters

In xEVs, inverters drive the electric motors (see Figure 4). An inverter is the heart of the electric drivetrain and falls squarely in the "too important to fail" category of the BOM. To minimize the possibility of critical failure, inverters in xEVs log motor position, current, voltage, and temperature into the NVM. This falls into the category of predictive maintenance. In a black box use case, in the event of inverter failure, the NVM logs diagnostic related data for failure analysis. This is very critical in improving the future designs for better safety. The challenges include capturing real-time data instantly in a continuous fashion and retaining data on power-loss in an AEC-Q100 qualified memory. The memory should require minimal or no software overhead while having high reliability for automotive applications. In addition, the memory should have sufficient write-cycle endurance to continuously log data for 20 years.

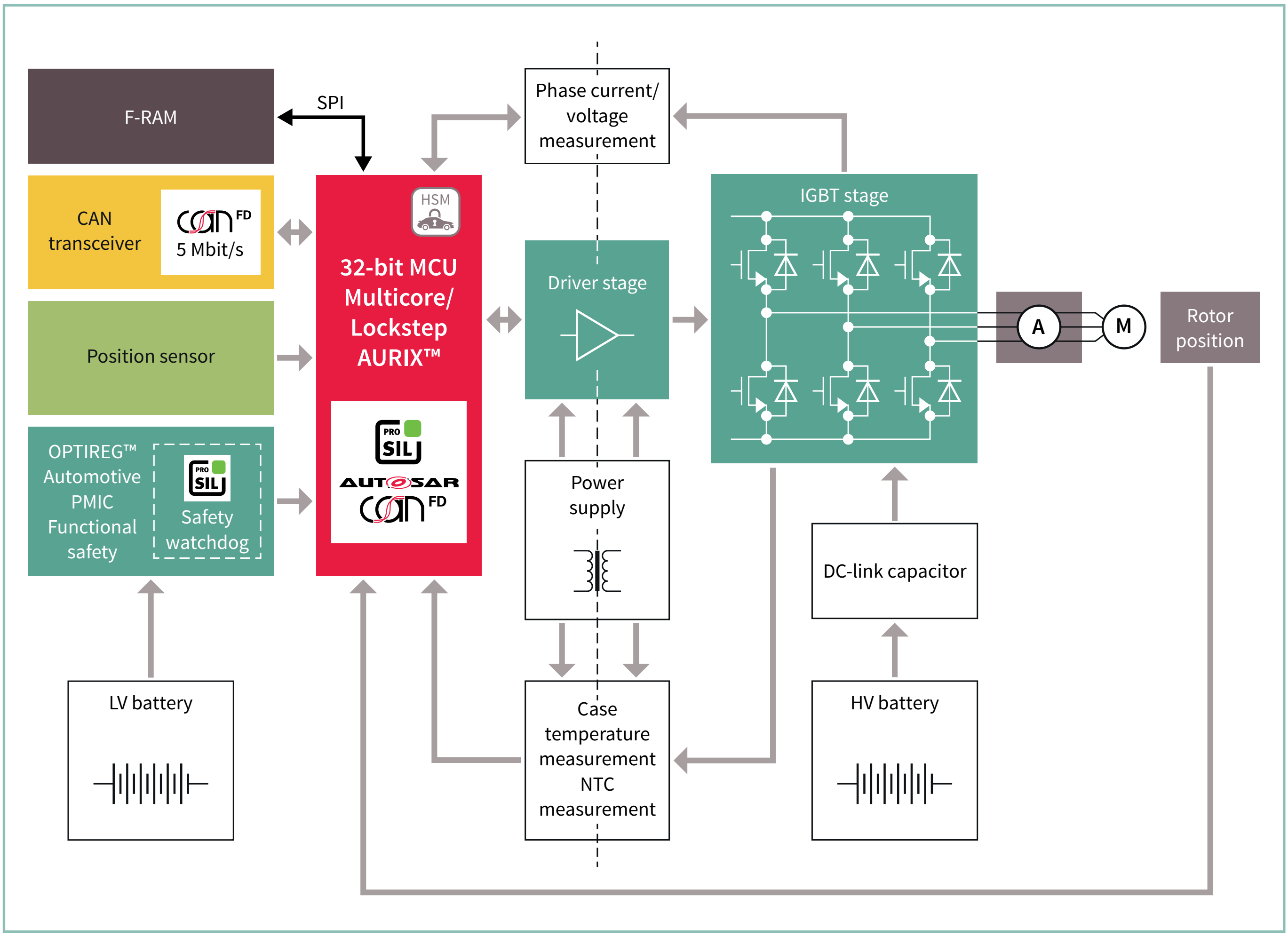

Figure 4: F-RAM usage in an xEV's main driver inverter.

The main challenges/requirements for the instantaneous and continuous memory storage in inverters can be summarized as :

- Log state variables and calibration data required for control algorithms
- Log diagnostic and fault codes like over current, over voltage, sensor fault, high temperature
- Implement rolling buffer to log high sampling rate (> 10 kHz) sensor data for fault detection or failure analysis. After an event, last few seconds or milliseconds of data can be retrieved to analyze the failure.

F-RAM: The details

F-RAM is a NVM which stores data as a polarization of a ferroelectric material (Lead-Zirconate-Titanate or PZT). As shown in Figure 5, down and up polarizations – effectively, changes in the atomic state of a positively charged ZrTi+ ion in the PZT crystal – create a hysteresis loop providing the ones and zeroes for digital storage.

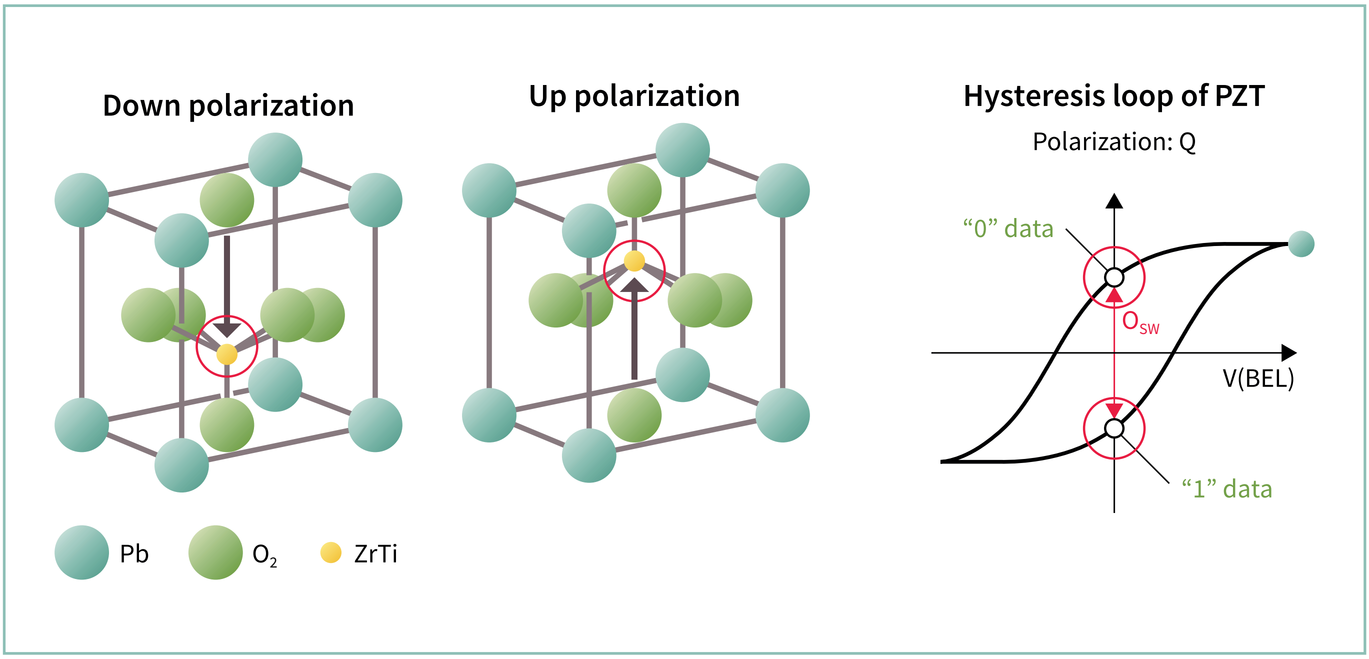

Figure 5: F-RAM is called "ferro" because ZrTi molecule follows a hysteresis loop.

Because of its molecular structure and symmetrical atomic position, F-RAM state transitions occur instantaneously and retain state in the absence of an electric field; in other words, it is instantly non-volatile. These transitions require inherently low switching energy. Consequently, F-RAMs are amongst the lowest power NVM technologies, consuming 200 times lesser energy than an EEPROM, and 3,000 times lesser energy than a comparable NOR Flash. Therefore, in critical data storage applications with fast writes, no data is at risk and highly reliable, ultra-low-energy data storage is provided.

These properties of F-RAM make it a far superior data-logging memory compared to EEPROM or Flash. Based on "atomic position" of F-RAM vs. the "trapped charge" operation of EEPROM and Flash memory, F-RAM provides Soft Error Rate (SER) immunity and is highly radiation tolerant.

The two symmetrical states mean minimal degradation with cycling over time so data retention of 100 years is possible.

Figure 6 shows a comparison of an F-RAM write cycle compared to EEPROM. With a Serial Peripheral Interface (SPI), F-RAM supports faster clock rates. Unlike EEPROM that sends an entire page of data, F-RAM writes only the necessary data. In addition, EEPROM requires a soak time at high (active) power to make data non-volatile. This is also called as time at risk because if power fails during this period, the entire data is lost. After this write process, the EEPROM status register must be read to verify the successful execution of the write operation. F-RAM on the other hand does not have any of these overheads delivering fast writes at considerably lower power consumption. F-RAM also means significantly lower software complexity.

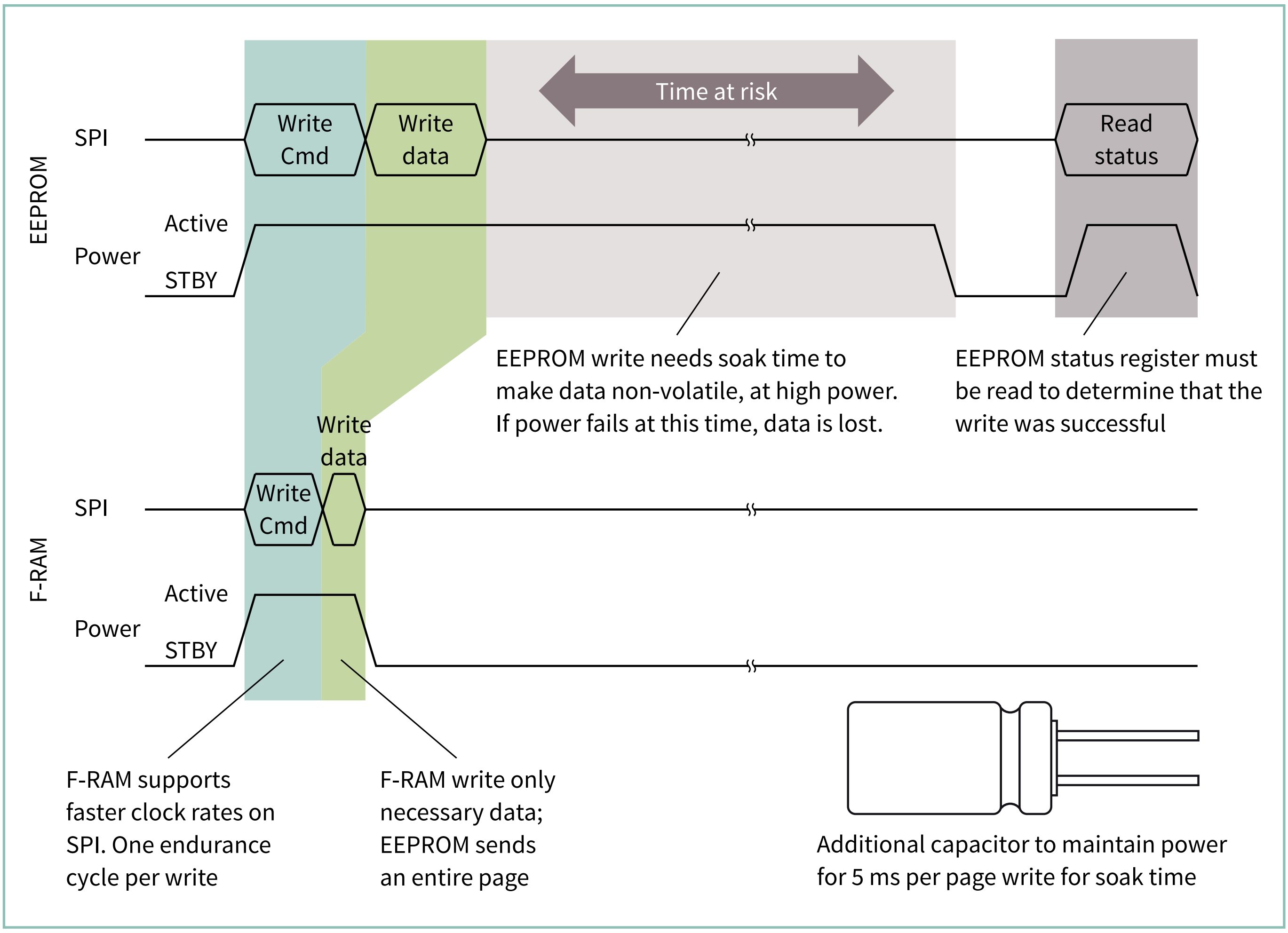

Figure 6: The F-RAM write cycle compared to an EEPROM write cycle identifies the key advantages of F-RAM technology.

In battery management systems, safety is paramount to prevent fire hazards which can lead to catastrophic events. In these systems non-volatile memory acts as a black box in case of a catastrophic event. Traditional memory like EEPROM or Flash is not usable for continuous storage of cell parameters due to its low endurance and slow write speeds. Hence systems which have EEPROM or Flash use volatile SRAM buffers for continuous storage of data. Data from SRAM is transferred to EEPROM or Flash periodically (ex: every hour or every ignition cycle to provide sufficient endurance). However, during an uncontrolled shutdown, transient data in SRAM is lost. This might result in loss of critical parameters like SOC/SOH and erroneous calculations in the next power-up that may lead to safety concerns. Hence it is an important design consideration to use F-RAM for data loss prevention due to catastrophic events like thermal runaway of the Li-Ion battery.

In contrast to EEPROM and Flash, F-RAM provides a fast write and low power memory solution for BMS with high reliability and high endurance. In summary, the benefits of F-RAM technology include:

› Zero-delay writes
› Low switching energy
› Virtually infinite endurance
› Long data retention
› High endurance without requiring any software overhead

Infineon F-RAM product offerings

With its inherent advantages over EEPROM and Flash memory, F-RAM is ideally suited for many automotive applications, including those required for xEVs. EXCELON™ F-RAM is Infineon's newest family of high-performance and high-reliability serial, non-volatile F-RAMs. This latest-generation of F-RAM memories include the AEC-Q100 qualified EXCELON™ Auto F-RAM option, with products starting from 128 kB (1 Mbit) up to 2 MB (16 Mbit) supporting high-speed, low-pin-count SPI and Quad SPI interfaces. Exclusively targeted at automotive applications like EDR, BMS and ADAS systems, EXCELON™ Auto F-RAMs can support harsh operating temperatures up to +125°C.

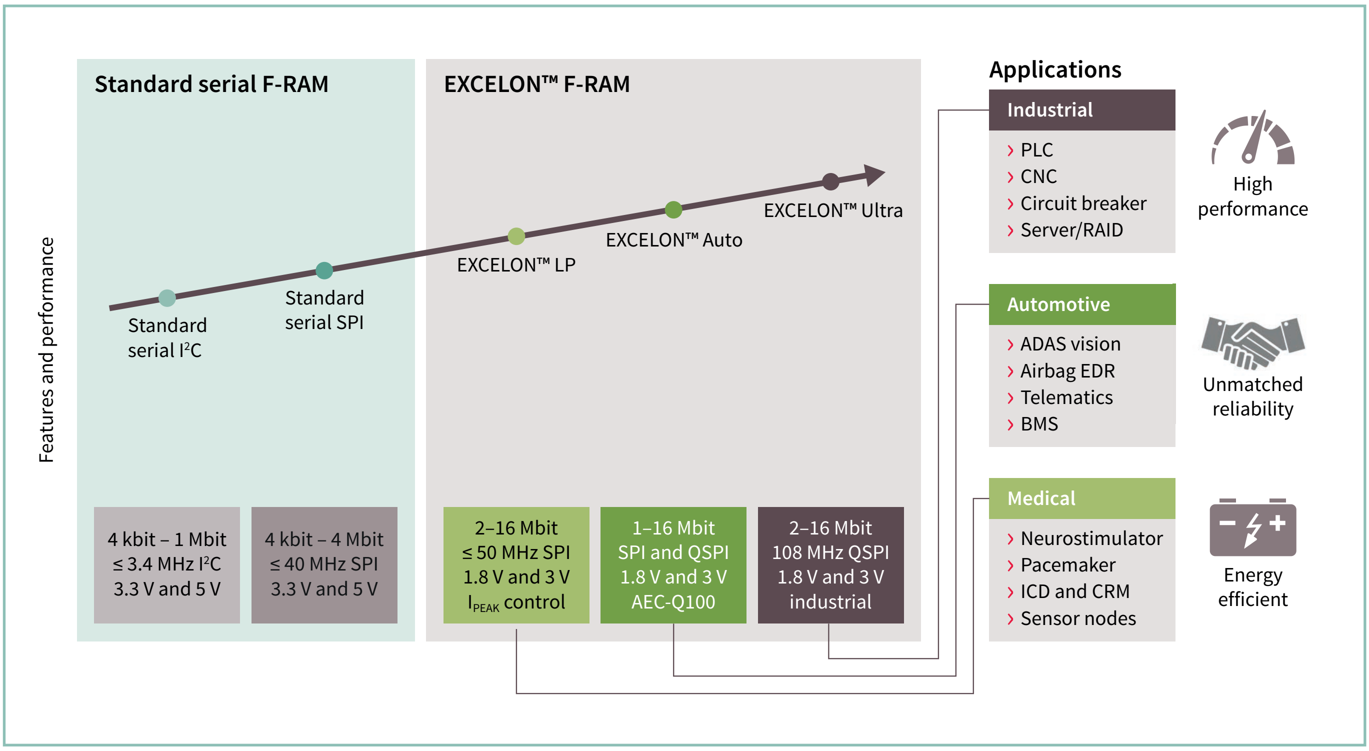

Figure 7

With its high-speed non-volatile data-logging capability, the F-RAM prevents data loss in critical and harsh automotive applications. Table 1 shows a comparison of key parameters of F-RAM to a typical EEPROM/Flash device.

Table 1: Comparison of typical non-volatile memories and F-RAM

		EEPROM/Data Flash	F-RAM
System level	Microcontroller	High internal RAM	Low internal RAM
	Storage energy	High	Low
	Backup capacitors	To support data storage during uncontrolled power-off	N/A
	Data scaling flexibility	Low	High
Component level	Write cycle	5–10 ms (page-wise)	Instant (Byte-wise)
	Write time[1] (16 kB)	1.3 s	3.2 ms
	Write energy[1] (16 kB)	27430 µJ	49 µJ
	Endurance	10^6 cycles	10^{14} cycles

1) EEPROM write current = 7 mA, SPI freq = 5 MHz, page size = 64, write time = 5 ms

Infineon Technologies' F-RAM portfolio includes products from 0.5 kB to 2 MB storage. Specific F-RAM product offerings are shown in Table 2 and Table 3. Both tables identify automotive products that have been AECQ-100 qualified to either 85°C, 105°C, or 125°C [2].

Table 2 Infineon's portfolio of low power and high endurance F-RAMs includes several automotive qualified serial and parallel-interface products.

Table 2: Infineon's portfolio of low power and high endurance F-RAMs includes several automotive qualified serial and parallel-interface products.

	LPC[1] F-RAM				Processor companion	Parallel F-RAM	
512 kb–16 Mb	**FM25V20A** **2 Mb**; 2–3.6 V 40 MHz SPI; Ind[2]	**CY15B104Q** **4 Mb**; 2–3.6 V 40 MHz SPI; Ind	**EXCELON™ [3] F-RAM** **Up to 16 Mb** **1.8 V,** **108 MHz QSPI[4]**			**FM22L16/LD16** **4 Mb**; 2.7–3.6 V 55 ns; x8; Ind	
	FM25V10/VN10 **1 Mb**; 2–3.6 V 40 MHz SPI; Ind	**CY15B102Q** **2 Mb**; 2–3.6 V 25 MHz SPI; Auto E[6]	**FM24V10/VN10** **1 Mb**; 2–3.6 V 3.4 MHz I^{2}C; Ind			**FM28V102A** **1 Mb**; 2–3.6 V 60 ns; x16; Ind	**FM28V202A** **2 Mb**; 2–3.6 V 60 ns; x16; Ind
	FM25V05 **512 kb**; 2–3.6 V 40 MHz SPI; Ind		**FM24V05** **512 kb**; 2–3.6 V 3.4 MHz I^{2}C; Ind			**CY15B101N** **1 Mb**; 2–3.6 V 60 ns; x16; Auto A, E	**CY15B102N** **2 Mb**; 2–3.6 V 60 ns; x16; Auto A, E
4–256 kb	**FM25V02A/W256** **256 kb**; V02A: 2–3.6 V W256: 2.7–5.5 V 40 MHz SPI; Ind	**CY15B256Q** **256 kb**; 3.3 V 33/40 MHz SPI; Auto A[5], E	**FM24V02A/W256** **256 kb**; V02A: 2–3.6 V W256: 2.7–5.5 V 3.4 MHz I^{2}C; Ind	**CY15B256J** **256 kb**; 2–3.6 V 3.4 MHz I^{2}C; Auto A, E		**FM28V020** **256 kb**; 2–3.6 V 70 ns; x8; Ind	**FM18W08** **256 kb**; 2.7–5.5 V 70 ns; x8; Ind
	FM25V01A **128 kb**; 2–3.6 V 40 MHz SPI; Ind	**CY15B128Q** **128 kb**; 3.3 V 33/40 MHz SPI; Auto A, E	**FM24V01A** **128 kb**; 2–3.6 V 3.4 MHz I^{2}C; Ind	**CY15B128J** **128 kb**; 2–3.6 V 3.4 MHz I^{2}C; Auto A, E	**FM31256/31(L)278** **256 kb**; 3.3, 5 V; 1 MHz I^{2}C; Ind; RTC; Power Fail; Watchdog; Counter	**FM1808B** **256 kb**; 5 V 70 ns; x8; Ind	**FM16W08** **64 kb**; 2.7–5.5 V 70 ns; x8; Ind
	FM25640B/CL64B **64 kb**; 3.3, 5 V 20 MHz SPI; Ind	**CY15B064Q/E064Q** **64 kb**; 3.3, 5 V 16/20 MHz SPI; Auto A, E	**FM24C64/CL64** **64 kb**; 3.3, 5 V 1 MHz I^{2}C; Ind	**CY15B064J/E064J** **64 kb**; 3.3, 5 V 1 MHz I^{2}C; Auto A, E	**FM3164/31(L)276** **64 kb**; 3.3, 5 V; 1 MHz I^{2}C; Ind; RTC; Power Fail; Watchdog; Counter		
	FM25C160/L16 **16 kb**; 3.3, 5 V 20 MHz SPI; Ind	**CY15B016Q/E016Q** **16 kb**; 3.3, 5 V 16/20 MHz SPI; Auto A, E	**FM24C16/CL16** **16 kb**; 3.3, 5 V 1 MHz I^{2}C; Ind	**CY15B016J/E016J** **16 kb**; 3.3, 5 V 1 MHz I^{2}C; Auto A, E			
	FM25040/L04 **4 kb**; 3.3, 5 V 20 MHz SPI; Ind	**CY15B004Q/E004Q** **4 kb**; 3.3, 5 V 16/20 MHz SPI; Auto A, E	**FM24C04/CL04** **4 kb**; 3.3, 5 V 1 MHz I^{2}C; Ind	**CY15B004J/E004J** **4 kb**; 3.3, 5 V 1 MHz I^{2}C; Auto A, E			

1) Low-pin-count
2) Industrial grade -40°C to +85°C
3) Ultra-low-energy
4) Quad serial peripheral interface
5) AEC-Q100 -40°C to +85°C
6) AEC-Q100 -40°C to +125°C

	Concept	Development	Sampling	Production
Status				
Availability			QQYY	QQYY
EOL (Last-Time-Ship)				QQYY
Automotive				

Table 3: Infineon's portfolio of ultra-low power, high speed and high endurance EXCELON™ F-RAMs includes several automotive qualified products.

	EXCELON™ Auto		EXCELON™ Ultra		EXCELON™ LP	
1–16 Mb	**CY15B116QSN** **16 Mb**; 1.8–3.6 V 24-ball FBGA 108 MHz QSPI[1] Auto S[2]	**CY15V116QSN** **16 Mb**; 1.71–1.89 V 24-ball FBGA 108 MHz QSPI Auto S	**CY15B116QSN** **16 Mb**; 1.8–3.6 V 24-ball FBGA 108 MHz QSPI, Ind[3], Ind Q	**CY15V116QSN** **16 Mb**; 1.71–1.89 V 24-ball FBGA 108 MHz QSPI, Ind, Ind Q	**CY15B116QI/N** **16 Mb**; 1.8–3.6 V 24-ball FBGA 20/40 MHz SPI, Comm[4], Ind	**CY15V116QI/N** **16 Mb**; 1.71–1.89 V 24-ball FBGA 20/40 MHz SPI, Comm, Ind
	CY15B116QN **16 Mb**; 1.8–3.6 V 24-ball FBGA 40 MHz SPI; Auto A[5]	**CY15V116QN** **16 Mb**; 1.71–1.89 V 24-ball FBGA 40 MHz SPI Auto A				
	CY15B108QSN **8 Mb**; 1.8–3.6 V 24-ball FBGA 108 MHz QSPI; Auto S	**CY15V108QSN** **8 Mb**; 1.71–1.89 V 24-ball FBGA 108 MHz QSPI Auto S	**CY15B108QSN** **8 Mb**; 1.8–3.6 V 24-ball FBGA 108 MHz QSPI, Ind, Ind Q	**CY15V108QSN** **8 Mb**; 1.71–1.89 V 24-ball FBGA 108 MHz QSPI, Ind, Ind Q	**CY15B108QN** **8 Mb**; 1.8–3.6 V 24-ball FBGA 50 MHz SPI, Ind, Ind Q[7]	**CY15V108QN** **8 Mb**; 1.71–1.89 V 24-ball FBGA 50 MHz SPI, Ind, Ind Q
	CY15B208QN **8 Mb**; 1.8–3.6 V 24-ball FBGA 40 MHz SPI; Auto E[6]	**CY15V208QN** **8 Mb**; 1.71–1.89 V 24-ball FBGA 40 MHz SPI Auto E	**CY15B108QSN** **8 Mb**; 1.8–3.6 V 8-pin GQFN, SOLIC 108 MHz QSPI, Ind	**CY15V108QSN** **8 Mb**; 1.71–1.89 V 8-pin GQFN, SOLIC 108 MHz QSPI, Ind	**CY15B108QI/N** **8 Mb**; 1.8–3.6 V 8-pin GQFN 20/40 MHz SPI, Comm, Ind	**CY15V108QI/N** **8 Mb**; 1.71–1.89 V 8-pin GQFN 20/40 MHz SPI, Comm, Ind
	CY15B204QN **4 Mb**; 1.8–3.6 V 8-pin SOIC 40 MHz SPI; Auto E	**CY15V204QN** **4 Mb**; 1.71–1.89 V 8-pin SOIC 40 MHz SPI Auto E				
	CY15B104QN **4 Mb**; 1.8–3.6 V 8-pin SOIC 50 MHz SPI; Auto A	**CY15V104QN** **4 Mb**; 1.71–1.89 V 8-pin SOIC 50 MHz SPI Auto A	**CY15B104QSN** **4 Mb**; 1.8–3.6 V 8-pin GQFN, SOLIC 108 MHz QSPI, Ind	**CY15V104QSN** **4 Mb**; 1.71–1.89 V 8-pin GQFN, SOIC 108 MHz QSPI, Ind	**CY15B104QI/N** **4 Mb**; 1.8–3.6 V 8-pin GQFN, SOIC 20/50 MHz SPI, Comm, Ind	**CY15V104QI/N** **4 Mb**; 1.71–1.89 V 8-pin GQFN, SOIC 20/50 MHz SPI, Comm, Ind
	CY15B102QN **2 Mb**; 1.8–3.6 V 8-pin SOIC 50 MHz SPI; Auto E	**CY15V102QN** **2 Mb**; 1.71–1.89 V 8-pin SOIC 50 MHz SPI Auto E	**CY15B102QSN** **2 Mb**; 1.8–3.6 V 8-pin SOIC 108 MHz QSPI, Ind	**CY15V102QSN** **2 Mb**; 1.71–1.89 V 8-pin SOIC 108 MHz QSPI, Ind	**CY15B102QN/QM** **2 Mb**; 1.8–3.6 V 8-pin DFN, SOIC 50 MHz SPI, Ind	**CY15V102QN** **2 Mb**; 1.71–1.89 V 8-pin DFN, SOIC 50 MHz SPI, Ind
	CY15B201QN **1 Mb**; 1.8–3.6 V 8-pin SOIC 50 MHz SPI; Auto E	**CY15V201QN** **1 Mb**; 1.71–1.89 V 8-pin SOIC 50 MHz SPI Auto E				

1) Quad serial peripheral interface
2) AEC-Q100 -40°C to +105°C
3) Industrial grade -40°C to +85°C
4) Commercial grade 0°C to +70°C
5) AEC-Q100 -40°C to +85°C
6) AEC-Q100 -40°C to +125°C
7) Industrial Q grade -40°C to +105°C

	Concept	Development	Sampling	Production
Status				
Availability			QQYY	QQYY
EOL (Last-Time-Ship)				QQYY
Automotive				

It is important to note that in contrast to EEPROM specified with an 85°C operating environment, F-RAM's capability to withstand 125°C means that its write endurance and data retention hold up better – even when the operating temperature increases. In summary, Infineon's EXCELON™ F-RAM provides:

- Instant data capture. No software/firmware overhead.
- Low power memory
- Endurance for 100 trillion write-cycles to log data at 10 µs for 20 years
- Data retention for 100 years
- AEC-Q100 qualified memory

A lifetime of memories

F-RAM's exceptional capabilities make it particularly suited for many critical applications. Automotive is well-known for its long-life requirements to satisfy customers for over 10 years or 100,000-miles, whichever comes first. With data retention for 100 years and 100 trillion write-cycles endurance capability for 20 years, the timing is right for design-in of F-RAM with its proven benefits to many new designs or significant changes occurring to existing xEV designs. As part of Infineon Technologies' extensive portfolio of automotive qualified technologies, F-RAM will play an integral role in the emerging next generation of automotive vehicles, especially xEVs.

References

[1] https://www.lucintel.com/feram-market.aspx
[2] https://www.infineon.com/cms/en/product/memories/f-ram-ferroelectric-ram/

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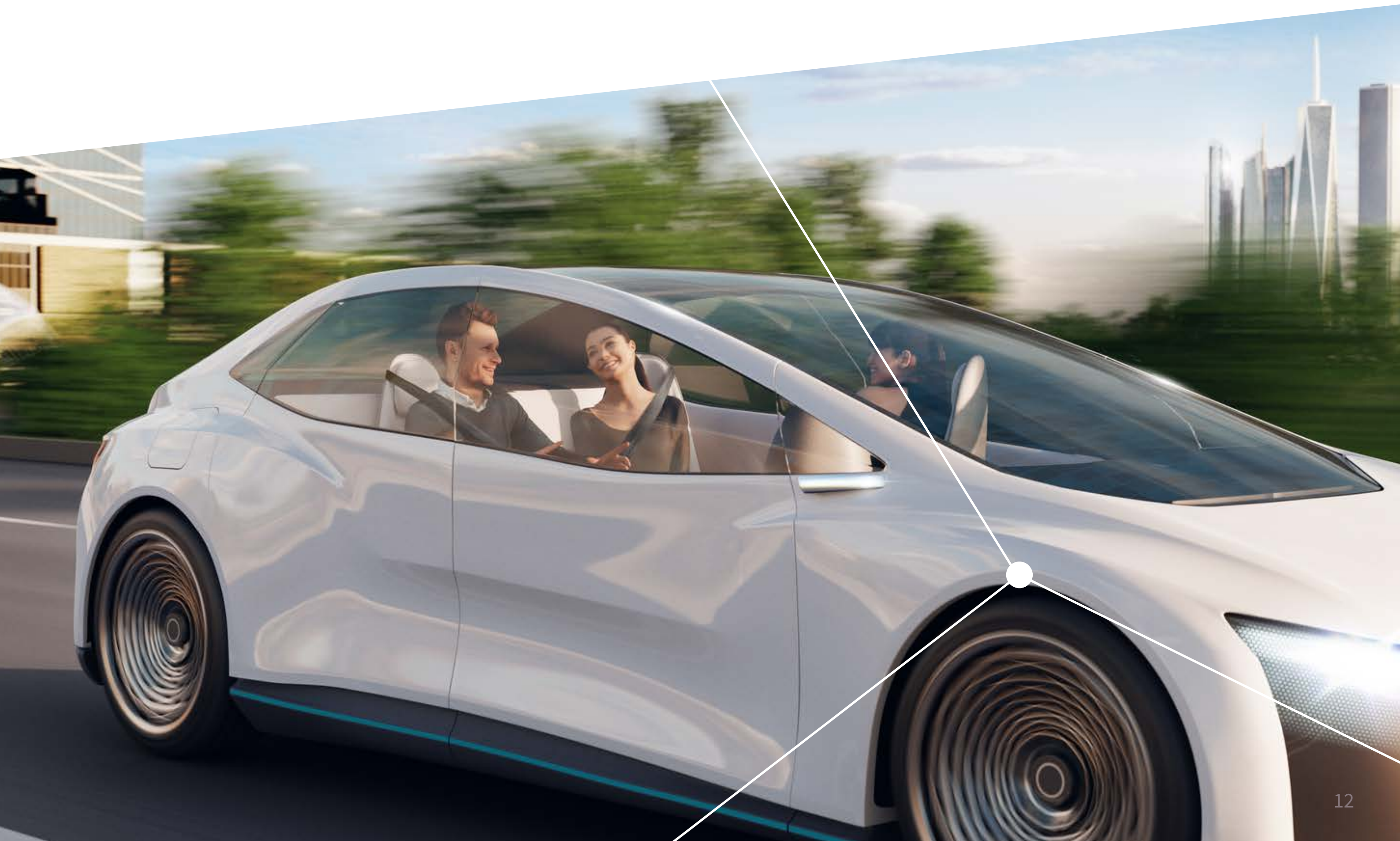

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