# MRAM's Journey to Becoming a Mainstream Memory

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Magnetoresistive random access memory (MRAM) has the potential to outperform traditional semiconductor memories because of its high speed, robust endurance, and system power savings. Since the first commercial MRAM was launched in 2006, the memory capacity and market size have greatly expanded [1]. In 2019, there were two landmark events in the history of MRAM: Everspin reached a major milestone by launching a 1Gb product [2], and three major foundries and two other companies announced the availability of products. These indicate that MRAM is a promising candidate for a mainstream memory technology. In this paper, we focus on the technologies for MRAM commercialization [1]: introducing current MRAM products and their technologies, discussing technological challenges for the next generation products, and reviewing new magnetization switching mechanisms from the product point of view.

The first commercial MRAM utilized the toggle mode of magnetic field switching and was brought to volume manufacturing by Freescale Semiconductor in 2006 as a 4 Mb discrete part. Since then, Everspin, a spinoff from Freescale, has further developed toggle MRAM and brought to the market a range of parts from 128 kb to 32 Mb which are used in applications such as storage, RAIDs, factory automation, IoT, and smart energy across commercial, industrial, automotive, and aerospace environments.

Spin-transfer torque (STT) switching offers an attractive solution for scaling to higher densities while lowering the write current per bit. Everspin commercialized a 64 Mb STT-MRAM in 2015 using in-plane magnetic tunnel junctions (iMTJs). The scalability of STT-MRAM has since been proven beyond the laboratory; MTJs with perpendicular magnetic anisotropy (pMTJ) were being developed to allow even lower writing current and higher density. In 2017, a discrete 256 Mb STT-MRAM part using pMTJs became commercially available followed by a 1 Gb STT-MRAM part in 2019 [2]. These discrete STT-MRAM are being deployed as non-volatile write buffer memory in solid state drives. STT-MRAM has also found applications in embedded memories where eFlash and SRAM face scaling difficulties.

Further scaling of STT-MRAM has been extensively studied, and the results are promising. We will discuss four factors for STT-MRAM scaling, including data retention, switching current density, switching efficiency, and cycling endurance, and discuss aspects of scaling which still need to be clarified in the future.

[1] S. Ikegawa, F. B. Mancoff, J. Janesky, and S. Aggarwal, "Magnetoresistive random access memory: present and future," *IEEE Trans. Electron Devices*, vol. 67, no. 4, pp. 1407-1419, Apr. 2020.

[2] S. Aggarwal et al., "Demonstration of a reliable 1 Gb standalone spin-transfer torque MRAM for industrial applications," in *IEDM Tech. Dig.*, Dec. 2019, pp. 2.1.1-2.1.4.