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Evolution of Apple's "A" Series Processors

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ABSTRACT
Apple's known to be a company which embraces in-house technology. While other companies outsource, Apple likes to keep things in-house whenever potential and therefore the chips found in iOS devices are no exception whereas other smartphones makers rely on Qualcomm, Mediatek and Intel for chipsets. Apple houses its own team of engineers to work on designs exclusive to their devices and it all began in 2008 when Apple purchased a small semiconductor company called P. A. Semi (i.e. Palo Alto Semiconductor). With a continuous thrive to push the human race forward, Apple's been exploiting the smartphones industry to the very limits possible. The first "Systems on Chip" (SoC) was used in the first iPhone in 2007 it was called the APL0098. A12X, which is the latest chipset by Apple, stands out to be the most advanced processor ever found on a Smartphone. The latest generation of Apple processors are manufactured by TSMC

Keywords – Apple Processors, Face ID, FinFET, System on Chip (SoC), Touch ID,

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I. INTRODUCTION

With the advancement in digital age, Apple has been developing a various "System on Chip" (SoC) and "System in Package" (SiP) processors to power mobile consumer devices and other tasks [1]. Before the introduction of the Apple "A" series of SoCs, Apple utilized a few SoCs in early versions of the iPhone and iPod touch. They were determined by Apple and manufactured by Samsung. They integrated a stand-alone ARM-based processing core(CPU), a graphics processing Unit(GPU), and other hardware required to give versatile processing capacities inside a solitary physical bundle. The "A" series of Apple processors is a family of "Systems on Chip" (SoC) utilized in the iPhone, iPad, iPod touch, and Apple TV. Within a single physical package, they integrated a combination of one or more ARM-based process cores (CPU), a graphics processing unit (GPU), cache memory and some other electronics required to cater for mobile computing functions. [1].

I. THE PRE "A" SERIES PHASE

The first ever A series processor chip were introduced in Apple's iPad tablet, followed by iPhone 4 and 4th generation iPod touch. Prior to this, APL0098, APL0278, APL0298, APL 2298 were used in the earlier iPhones. All of these used Package on Package (PoP) chipsets based on ARM architecture combined with PowerVR graphics chipset. The original iPhone housed AAPL0298 with single thread clock speed of 0.41GHz. Successor to this was AAPL 0278, introduced in September 2008 during the launch of 2nd generation iPod touch. It had 533MHz single core ARM 11 CPU combined with PowerVR MBX Lite GPU. It was manufactured by Samsung on a 65nm process. The AAPL0298 was introduced in June 2008 at the launch of iPhone 3GS, which had a single Cortex-A8 CPU along with PowerVR SGX535 GPU. AAPL2298 is 45nm shrunk version of iPhone 3GS SoC introduced on September, 2007.

Model No.	APL0098	APL0278	APL0298	APL2298
Introduced	June 2007	September 2008	June 2009	September 2009
Semiconductor Technology	90nm	65nm	65nm	45nm
CPU ISA (Instruction Set Architecture)	ARMv6	ARMv6	ARMv7	ARMv7
CPU	412 MHz single-core ARM 11	412-533 MHz single-core ARM 11	600 MHz single-core Cortex-A8	600-800 MHz single-core Cortex-A8
CPU Cache	L1i: 16 KB L1d: 16 KB	L1i: 16 KB L1d: 16 KB	L1i: 32 KB L1d: 32 KB L2: 256 KB	L1i: 32 KB L1d: 32 KB L2: 256 KB
GPU	PowerVR MBX Lite	PowerVR MBX Lite	PowerVR SGX535	PowerVR SGX535
Memory Technology	16-bit Single-channel 133 MHz LPDDR (533 MB/sec)	32-bit Single-channel 133 MHz LPDDR (1066 MB/sec)	32-bit Single-channel 200 MHz LPDDR (1.6 GB/sec)	32-bit Single-channel 200 MHz LPDDR (1.6 GB/sec)
Utilizing Devices	iPhone (1st gen.) iPod Touch (1st gen.) iPhone 3G	iPod Touch (2nd gen.) iPod Nano (4th gen.)	iPhone 3GS	iPod Touch (3rd gen.)

Fig 1 Processors used prior to introduction of A series processors

II. THE PHASE OF "A" SERIES PROCESSORS

Technically, A4 processor was the first Apple "A" series processor combined with ARM cortex A8 CPU with Power VR 535 GPU. It was used in iPad than in iPhone 4, 4th generation iPod touch and 2nd generation Apple TV. The first version clocked at 1GHz for the iPad was built on Samsung's 45nm chip fabrication process. For iPhone 4 and iPod touch 4th generation, the clock speed was reduced 800MHz to save battery life. [2]

In 2011, Apple revealed A5 chipset in the release of iPad 2 and later that year, the same chipset was included in iPhone 4s. Compared to the chipset A4, A5 was twice as fast and had up to nine times graphics performance. CPU present on A5 was a dual core ARM Cortex-A9 CPU coupled with ARM's advanced SIMD extension and GPU present on A5 was a dual core PowerVR SGX543MP2 GPU [1]. Its clock frequency was set to be at 1GHz in iPad 2 and was capable of dynamically adjust its frequency for saving battery life [2]. iPhone 4s had the same chipset clocked at 800MHz. The process size of the chipset was same as that of A4 i.e. 45nm. Third generation Apple TV, iPad Mini and the new version of iPad 2 were integrated with an upgraded version of A5 which had a process size of 32nm.

A5x was a follow up and high-performance variant of A5 and Apple averred that it has twice the graphics performance observed in A5. A5X witnessed a quad core GPU (PowerVR SGX543MP4) as compared to previous generation dual-core. It also had a quad channel memory bandwidth of 12GB/sec which was about more three times as compared to A5 [2]. It had dual Cortex-A9 cores to operate at frequency of 1GHz and was used in third generation iPad.

A6 was launched in the year 2012 was used in iPhone 5 and a year later in iPhone 5c respectively. Apple claimed that it was twice as fast and had up to twice the graphics performance compared to its predecessor. Apple-designed Cortex-A7 was clocked at 1.3GHz and 266MHz triple core PowerVR SGX 543MP3 GPU. Samsung manufactured it on a high-κ metal gate 32 nm process.

A6x was launched in the same year as of A6 and was featured on fourth generation iPad. With twice the CPU performance and twice graphics performance than its predecessor, it used same dual-core Swift CPU, however had a brand-new GPU, quad Channel memory channel and a clock rate of 1.4GHz. It included a quad-core PowerVR SGX 554MP4 GPU clocked at 300MHz and a quad-channel memory scheme. Samsung manufactured it on a high-κ metal gate 32 nm process. [1]

Name	**A4**	**A5**	**A5**	**A5**	**A5X**	**A6**	**A6X**
Model No.	APL0398	APL0498	APL2498	APL7498	APL5498	APL0598	APL5598
Semiconductor Technology	45 nm	45 nm	32 nm HKMG	32 nm HKMG	45 nm	32 nm HKMG	32 nm HKMG
CPU ISA (Instruction Set Architecture)	ARMv7	ARMv7	ARMv7	ARMv7	ARMv7	ARMv7s	ARMv7s
CPU	0.8–1.0 GHz single-core Cortex-A8	0.8–1.0 GHz dual-coreCortex-A9	0.8–1.0 GHz dual-coreCortex-A9	Single-coreCortex-A9	1.0 GHz dual-core Cortex-A9	1.3 GHz dual-coreSwift	1.4 GHz dual-core Swift
CPU Cache	L1i: 32 KB L1d: 32 KB L2: 512 KB	L1i: 32 KB L1d: 32 KB L2: 1MB	L1i: 32 KB L1d: 32 KB L2: 1 MB	L1i: 32 KB L1d: 32 KB L2: 1 MB	L1i: 32 KB L1d: 32 KB L2: 1 MB	L1i: 32 KB L1d: 32 KB L2: 1 MB	L1i: 32 KB L1d: 32 KB L2: 1 MB
GPU	PowerVR SGX535	PowerVR SGX543MP2 (dual-core) @ 200 MHz (12.8 GFLOPS)	PowerVR SGX543MP2 (dual-core) @ 200 MHz (12.8 GFLOPS)	PowerVR SGX543MP2 (dual-core) @ 200 MHz (12.8 GFLOPS)	PowerVR SGX543MP4 (quad-core) @ 200 MHz (25 GFLOPS)	PowerVR SGX543MP3 (triple-core) @ 266 MHz (25.5 GFLOPS)	PowerVR SGX554MP4 (quad-core) @ 266 MHz (68.1 GFLOPS)
Memory Technology	32-bit Dual-channel 200 MHz LPDDR (3.2 GB/sec)	32-bit Dual-channel400 MHz LPDDR2-800 (6.4 GB/sec)	32-bit Dual-channel400 MHz LPDDR2-800 (6.4 GB/sec)	32-bit Dual-channel400 MHz LPDDR2-800 (6.4 GB/sec)	32-bit Quad-channel400 MHz LPDDR2-800 (12.8 GB/sec)	32-bit Dual-channel533 MHz LPDDR2-1066(8.528 GB/sec)	32-bit Quad-channel533 MHz LPDDR2-1066 (17.1 GB/sec)
Utilizing Devices	iPad (1st gen.) iPhone 4 iPod Touch (4th gen.) Apple TV (2nd gen.)	iPad 2 iPhone 4s	Apple TV (3rd gen.) iPad 2 (iPad2,4) iPod Touch (5th gen.) iPad Mini (1st gen.)	Apple TV (3rd gen.) (Apple TV3,2)	iPad (3rd gen.)	iPhone 5 iPhone 5c	iPad (4th gen.)

Fig 2 Processors used prior to introduction of Touch ID

III. INTRODUCTION OF TOUCH ID

Fig 3 Logo used for Touch ID convention [3]

A fingerprint recognition feature designed and released by Apple Inc. was named as Touch ID. It has featured in the all the iPhones from iPhone 5s to iPhone 8 and 8 plus. It allows to unlock iPhone and also to make various purchases on the App Store, iTunes Store and Apple Books Store. Apple introduced faster second-generation Touch ID in iPhone 6s [3].

iPhone 5s was launched in the 2013 which featured A7 chipset. The iPad Air, iPad Mini 2 and iPad Mini 3 were also powered by the A7 chipset. Comapiring it to A6, A7 had two times the graphics power and was twice as fast [2]. A7 was the first chipset to feature 64–bit CPU instead of 32bit [2] which means the processor could handle more data at once. It had a CPU which was Apple-designed [1] 1.3-1.4GHz ARMv8-A dual core CPU named Cyclone, and an integrated PowerVR GX6450 GPU in a four cluster configuration. Similar to all the previous versions, A7 was also manufactured by Samsung on high-κ metal gate 28 nm process. [2].

Apple A8 was a package on package 64-bit system which made its appearance in iPhone 6 and 6 plus in the year 2014. A year later, it was also used in iPad mini 4. Apple claimed that it had 25% more CPU performance 50% more graphics performance as compared to Apple A7. It had a CPU which was Apple-designed 1.4GHz 64-bit ARMv8-A dual-core CPU, and an integrated PowerVR GX6450 GPU in a four-cluster configuration. Replacing Samsung as a manufacturer of Apple mobile device processors, the A8 was manufactured on a 20-nm process by TSMC [1].

With the launch of iPad Air 2 in the year 2014, Apple introduced A8X, a high-performance variant of Apple A8. It had 40% more CPU performance and 2.5times the graphics performance of its predecessor, the Apple A7. The Apple A8X utilizes a triple core CPU, a new octa-core CPU, a dual channel memory and 1.5GHz CPU clock rate. It was integrated with an octa-core PowerVR GXA6850 GPU clocked at 450MHz. It had 3 billion transistors and was manufactured by TSMC on their 20nm fabrication process. [1]

Year 2015 witnessed the launched of Apple A9 which was used in iPhone 6S and 6S Plus. On comparing it to A8, it had 70% more CPU performance and 90% more graphics performance. First time for a Apple Soc, it was dual sourced; TSMC manufactured it on their 16nm FinFET process and Samsung manufactured it on their 14nm FinFET LPE process. It also featured in iPhone SE and iPad (2017) [1].

A9X was the successor of A9 and made its appearance with the introduction of iPad Pro in the year 2015. As it was the successor of A9, it had 80% more CPU power and twice the GPU performance. TSMC manufactured it on their 16nm FinFET process [2].

Apple Inc., introduced A10 Fusion 64-bit ARM based system on chip (SoC) in September 2016 and was used in iPhone 7 and 7 Plus. Apple used the same chip in iPad (2018). It had new quad core design with two high performance cores, and two efficient cores. It was manufactured by TSMC on their 16nm FinFET process.

In June 2017, Apple Inc., announced release of 10.5” iPad Pro and second generation of 12.9” iPad Pro. Both of these models had Apple A10X Fusion chipset. A10X Fusion is a 64-bit ARM based system on chip (SoC) designed by Apple Inc. Apple claimed that it had 30% faster CPU and 40% faster GPU than its predecessor, the A9X. It was manufactured by TSMC on their 10nm FinFET process.

Name	A7	A7	A8	A8X	A9	A9X	A10 Fusion	A10X Fusion
Model No.	APL0698	APL5698	APL1011	APL1012	APL0898 APL1022	APL1021	APL1W24	APL1071
Semiconductor Technonogy	28 nmHKMG	28 nmHKMG	20 nm(TSMC)	20 nm(TSMC)	14 nm FinFET(Samsung) 16 nm FinFET (TSMC)	16 nm FinFET(TSMC)	16 nm FinFET(TSMC)	10 nm FinFET(TSMC)
CPU ISA	ARMv8-A	ARMv8-A	ARMv8-A	ARMv8-A	ARMv8-A	ARMv8-A	ARMv8-A	ARMv8-A
CPU	1.3 GHz dual-coreCyclone	1.4 GHz dual-coreCyclone	1.1–1.5 GHz dual-coreTyphoon	1.5 GHz triple-coreTyphoon	1.85 GHz dual-coreTwister	2.16–2.26 GHz dual-coreTwister	2.34 GHz quad-core (2x Hurricane + 2x Zephyr)	2.36 GHz hexa-core (3x Hurricane + 3x Zephyr)
CPU Cache	L1i: 64 KB L1d: 64 KB L2: 1 MB L3: 4 MB (inclusive)	L1i: 64 KB L1d: 64 KB L2: 1 MB L3: 4 MB (inclusive)	L1i: 64 KB L1d: 64 KB L2: 1 MB L3: 4 MB (inclusive)	L1i: 64 KB L1d: 64 KB L2: 2 MB L3: 4 MB (inclusive)	L1i: 64 KB L1d: 64 KB L2: 3 MB L3: 4 MB (Victim)	L1i: 64 KB L1d: 64 KB L2: 3 MB L3: none	L1i: 64 KB L1d: 64 KB L2: 3 MB L3: 4 MB	L1i: 64 KB L1d:64 KB L2: 8 MB L3: none
GPU	PowerVR G6430(quad-core) @ 450 MHz (115.2 GFLOPS)	PowerVR G6430(quad-core) @ 450 MHz (115.2 GFLOPS)	PowerVR GX6450(quad-core)@ ~533 MHz (136.5 GFLOPS)	PowerVR GXA6850(octa-core) @ ~450 MHz (230.4 GFLOPS)	PowerVR GT7600(hexa-core)@ ~600 MHz (230.4 GFLOPS)	PowerVR 7XT Series(dodeca-core) @ ~533 MHz (409.3 GFLOPS)	PowerVR GT7600 Plus(hexa-core) @ >650 MHz (>250 GFLOPS)	PowerVR GT7600 Plus (dodeca-core)
Memory Technology	64-bit Single-channel800 MHz LPDDR3-1600(12.8 GB/sec)	64-bit Single-channel800 MHz LPDDR3-1600(12.8 GB/sec)	64-bit Single-channel800 MHz LPDDR3-1600 (12.8 GB/sec)	64-bit Dual-channel800 MHz LPDDR3-1600 (25.6 GB/sec)	64-bit Single-channel1600 MHz LPDDR4-3200(25.6 GB/sec)	64-bit Dual-channel1600 MHz LPDDR4-3200 (51.2 GB/sec)	64-bit Single-channel1600 MHz LPDDR4(25.6 GB/sec)	64-bit Dual-channel1600 MHz LPDDR4 (51.2 GB/sec)
Utilizing Devices	iPhone 5S iPad Mini 2 iPad Mini 3	iPad Air (1st gen.)	iPhone 6 iPhone 6 Plus iPod Touch (6th gen) iPad Mini 4 Apple TV (4th gen.) HomePod	iPad Air 2	iPhone 6S iPhone 6S Plus iPhone SE iPad (2017)	iPad Pro (12.9-inch) (1st gen.) iPad Pro (9.7-inch)	iPhone 7 iPhone 7 Plus iPad (2018)	iPad Pro (10.5-inch) iPad Pro (12.9-inch) (2nd gen.) Apple TV 4K

Fig 4 Processors used post introduction of Touch ID

IV. INTRODUCTION CHIPS WITH BIONIC, AI AND NEURAL NETWORK CAPABILITIES

Fig 5 FaceID logo [6]

Last year, Apple announced its much awaited A11 Bionic with internally built GPU, claimed to be 30% faster than the GPU used in iPhone 7 models. It has a 64-bit ARM based on system on chip(SoC) and two high performance cores stated to be 25% faster than Apple A10 and four energy-efficient cores 70% faster than the energy-efficient cores in A10[1]. It is coupled with Apple's all-new Neural Engine which is used to handle AI tasks such as Face Recognition, Animoji (a new feature introduced from iPhone X) and machine learning tasks. Motion coprocessor M11 is embed in A11 and also includes an image processor that supports computational photography functions namely advanced pixel processing, light estimation and wide color capture [5]. It is manufactured by TSMC using their 10 nm FinFET process and has 4.3 billion transistors, 30% smaller than A10.

In 2018, Apple released the iPhone XS, XS Max and XR, featuring the all-new A12 Bionic chipset. The two high performance cores present in A12, are about 15% faster than A11 Bionic. There are four high-efficiency cores in A12 which consume 50% less power than energy-efficient cores in A11 Bionic. For the time ever in a smartphone, it is manufactured using 7nm FinFET process, by TSMC [4].

A12X was also introduced in 2018 when apple showcased the newly designed line up of iPad pro models. It is a 64 –bit ARM –based system on a chip (SoC) designed by Apple Inc. It has four high performance cores and four high-efficiency cores. Again, it is manufactured by TSMC using 7nm FinFET process, which is the first ever in a tablet.

Name	A11 Bionic	A12 Bionic	A12X Bionic
Model No.	APL1W72	APL1W81	APL1083
Semiconductor Technology	10 nm FinFET(TSMC)	7 nm FinFET(TSMC)	7 nm FinFET(TSMC)
CPU ISA	ARMv8.2-A	ARMv8.3-A	ARMv8.3-A
CPU	2.39 GHz hexa-core (2x Monsoon + 4x Mistral)	2.49 GHz hexa-core (2x Vortex + 4x Tempest)	2.49 GHz octa-core (4x Vortex + 4x Tempest)
CPU Cache	L1i: 64 KB L1d: 64 KB L2: 8 MB L3: none	L1i: 128 KB L1d: 128 KB L2: 8 MB L3: none	L1i: 128 KB L1d: 128 KB L2: ? MB L3: none
GPU	Apple Custom GPU (triple-core)	Apple Custom GPU (quad-core)	Apple Custom GPU (hepta-core)
Memory Technology	64-bit Single-channel2133 MHz LPDDR4X (34,1 GB/sec)	64-bit Single-channel2133 MHz LPDDR4X (34,1 GB/sec)	64-bit Dual-channel2133 MHz LPDDR4X(68.2 GB/sec)
Utilizing Devices	iPhone 8 iPhone 8 Plus iPhone X	iPhone XS	iPad Pro (11.0-inch) iPad Pro (12.9-inch) (3rd gen.)

Fig 5 Processors which have capabilities of FaceID

V. CONCLUSION

Apple's been dominating in the mobile universe over the past 10 years with their revolutionary products. Embracing in-house technologies enables Apple Inc., to push the technologies to the very limits and their A series chipsets are a perfect example of their great work. Apple has successfully moved from outsourcing mobile chipsets to designing them in-house, whereas numerous other companies still rely on Qualcomm for their mobile chipsets. Apple keeps on exploiting more and more with each design iteration in the chipset that they design. The architectural changes that they make enables CPU to manage performance

by dynamically adjusting clock speed, processor and voltage and even disabling the whole CPU which undoubtedly enables Apple to lead ahead on the mobile planet.

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