A RISC-V Core System-on-Chip Based on SilTerra 110nm for Smartwatch Applications

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[[1]](#footnote-0) ***Abstract*—A rapid growth of smartwatch technology has created a demand for low power and high performance System-on-Chip (SoC) solutions. The small size of batteries and the ever increasing number of sensors contribute hugely to these factors. Other than that, the dominance shown by proprietary ISA on many of these devices has slowed down ability in customizing chips. Thus, new ideas and techniques could not be implemented by SoC designers, as they only can experiment within the given set of specifications. This project presents a RISC-V core System-on-Chip (SoC), specifically made for smartwatch applications, utilizing the process technology of SilTerra 110nm. This provides an opportunity to overcome limitation imposed by the proprietary ISA, and meet with the demands of modern smartwatches. Prior to design and implementation process, a review on commercial smartwatch is done to determine the specifications for smartwatch SoC. An energy efficient core of RISC-V is thoughtfully chosen to optimize power consumption and enhance overall performance. Results show that the proposed SoC has achieved 13.8 mW below the power target, while surpassing the performance target by 28 MHz. As a consequence, this serves as a solid foundation for further research and development in the future.**

***Index Terms*—ISA, RISC-V, System-on-Chip, SilTerra, Smartwatch**

# I. INTRODUCTION

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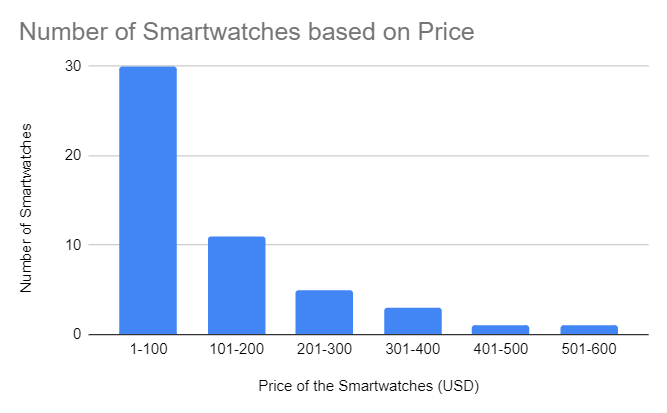
owadays, wearable devices like smartwatches are very popular. Smartwatch gives its user the ability to be connected, send, receive emails and messages, keep track of health and fitness, or even make calls on the go [1]. Currently, smart watches on the market can be divided into two types. Firstly, without a call feature, but achieves multi-functionality by connecting with smartphones and can synchronize phone calls, text messages, e-mail, photos, music etc. Secondly, with call functions and support SIM card, which simply is in the form of smart phone watch essentially [2]. Other than that, the functionality of smartwatches can be seen as twofold. First, the smartwatches act as communication and notification tools by complementing smartphones with features such as receiving notifications and performing micro interactions. Second, smartwatches also act to monitor some human physiological signals and biomechanics. For example, it may act as a fitness tracking device which helps the users to log their daily activities [3]. Today, smartwatches are used in various IoT scenarios including healthcare and fitness. In fact, current smartwatches are well equipped with a variety of sensors and heterogeneous wireless protocols. They are now using increasingly more powerful multi-core processors and wireless networks like 4G LTE [4]. In terms of the ISA, ISAs like ARM and x86 have dominated the world of microprocessor. Its closed source characteristic has led to a poor scalability and uncontrollable power consumption [5]. Nevertheless, with the recent rise of RISC-V ISA, this is all set to be changed in future. RISC-V is a free and open instruction set with well-structured modularity that provides high level of flexibility at a very low cost. It essentially allows users to produce custom chips that suit with their specific application [6].

This paper proposed a RISC-V core System-on-Chip which targeting smartwatch applications in order to achieve low power consumption while maintaining the overall performance. Based on our review, there is a variety in the price of smartwatch. In addition, a valuable discovery can be found by examining the commercial smartwatch SoCs in order to find out the power and performance target of our SoCs. Other than that, the basic requirement of digital peripherals for smartwatch can also be found to assemble an SoC. With this, we can fine-tune our SoC to comply with the current smartwatch requirement.

The paper is organized as follows. The review of smartwatch and SoC is explained in Section II.

# II. Review on smartwatch and soc

Before we can go deeper onto the simulation of smartwatch SoC, a review for the current commercial smartwatch is made to proposed an ideal architecture of smartwatch SoC. The review will start by surveying 51 commercial smartwatches. Table I, II, III show the system of smartwatch which consist of screen, physical dimension, operating system, system compatibility, battery capacity and battery lifetime. On the other hand, Table IV, V, VI, VII show the board of smartwatch which consist of microcontroller, size of bit, off-chip RAM, off-chip Storage, on-board sensors, and on-board RF. As we have found out the information of these, a category of smartwatch is selected based on the price. Fig 1 shows the number of smartwatches in our survey based on its price category.



**Fig. 1.** Smartwatch based on price category

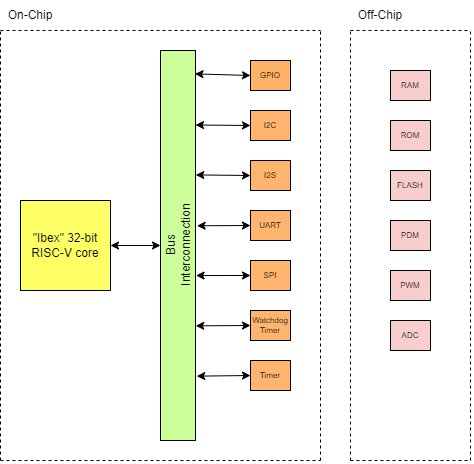
As the price range of 1-100 recorded the highest number of smartwatch in the review, a deep focus will be given in identifying the smartwatch SoC based on this price category. However, due to undisclosed data from some of the smartwatches, only the published data could be assessed especially on the SoC specifications and digital peripherals. Table VIII shows good indicator in determining the requirement of the power and performance needs of the smartwatch. Based on the findings, the lowest achievable frequency of smartwatch is indicate at **40MHz** and the highest power consumption is at **25.074mW.** These numbers are crucial in setting the benchmark target of our smartwatch SoC later on during the simulation.

On the other hand, Table IX shows the digital peripherals required for the smartwatch SoC. Based on the finding, we have found many similarities of digital peripherals which include I2C, I2S, SPI, UART, GPIO, PWM, PDM, Watchdog Timer, and Timer among all the observed smartwatch SoCs. Based on study in [7], by reducing hardware components, it can prolong the battery life and reduce the overall chip size. Thus, in this project a minimum number of components will be taken based on the Table IX, in order to keep the power consumption as low as possible while maintains the requirement of performance for smartwatch.

# III. Architecture of smartwatch SoC

In order to produce an architecture of smartwatch SoC, we have used the information based on Table IX. For the architecture, digital components of the SoC are include in the on-chip, and analog components of the SoC are included in the off-chip. One of the reasons that these components are separated is because only digital components can be simulated during the simulation.

To find out the RISC-V core for this SoC, study in [8] has suggested that zero-riscy core is an ideal core for a resource-constrained applications like smartwatch. Thus, it is ideal to ensure that our SoC can achieve low power consumption as possible to counter the problem of short battery life while maintain the overall performance. For the bus interconnection, APB is used to connect the digital peripherals which consist of I2C, I2S, SPI, UART, GPIO, PWM, PDM, Watchdog Timer, and Timer. For the off-chip components, it consist of RAM, ROM, Flash, ADC, PWM, and PDM. The proposed amount of size for each type of memory is 64kB, 128kB, and 512kB for RAM, ROM, and Flash memory respectively. Fig 2 shows the architecture of smartwatch SoC.

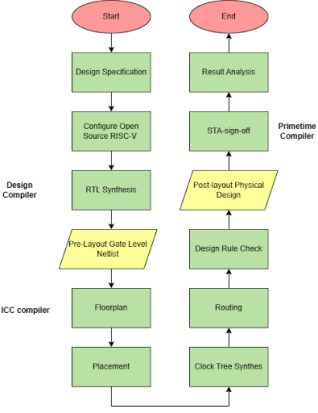


**Fig. 2.** Proposed Architecture of Smartwatch SoC

# IV. Methodology

Implementing a system-on-chip is not a simple task. It involves dealing with various complexities to successfully integrate multiple components and functionalities. For this process, it is called ASIC implementation. ASIC is very crucial as it integrates the memory compiler into the processor subsystem with the process technology of SilTerra 110nm. In this project, the system-on-chip will be simulated using the Synopsys tool. This tool provides many functionalities such as Design Compiler (DC), Integrated Circuit Compiler (ICC), and Prime-time Compiler. These are essential compilers in developing the System-on-Chip (SoC) for smartwatch.

For the first step it involves design specification. Design specification is essential in determining the architecture of smartwatch SoC. Next, it involves in configuring open source materials that can help to generate the verilog modules based on the proposed architecture. After that, the RTL will be synthesize to get the gate-level netlist. This is an important step before we move on to the physical design of the SoC. During the physical design, it involves floor-planning, placement, clock tree synthesis and routing, before static timing analysis (STA) is carried out at the sign-off validation. Fig 3, shows the flowchart of the ASIC implementation.



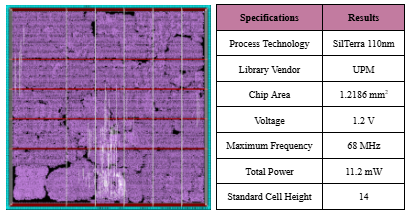
**Fig. 3..** Flowchart of the ASIC implementation

# V. Results and Discussion

As the architecture has been proposed, different voltages and standard cell height library are observed to achieve low power and high performance System-on-chip. Table X shows results of different voltages of our proposed architecture. Therefore, 1.2V has been set as our voltage because of the power and performance achieved are within our target. In order to produce significant performance, method of using different standard cell height library has also been utilized. Table Y provides evidence by increasing the heights of standard cell library, a higher performance can be achieved.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Configurations | SoC1 | SoC2 | SoC3 | SoC4 | SoC5 | SoC6 | SoC7 (Proposed) |
| Voltage | 0.4 | 0.6 | 0.8 | 1.2 | 1.2 | 1.2 | 1.2 |
| Standard Cell Heights | 7 | 7 | 7 | 7 | 9 | 12 | 14 |
| Total Power (µW) | 5.56 | 8.17 | 42.3 | 4110 | 6440 | 9150 | 11200 |
| Frequency (MHz) | 1 | 1 | 10 | 56 | 62 | 66 | 68 |
| Area (µm²) | 733 nm | 661 nm | 684 nm | 117 nm | 947 nm | 1032nm | 1221 nm |

With these specifications, the proposed SoC for smartwatch is shown in table Z. The ultimate objective is to select the best specifications which is below the power targeted value and above the minimum frequency for a smartwatch to operate.



**Fig. 4..** Physical Layout of the proposed smartwatch SoC

V. Conclusion

This paper proposed a smartwatch SoC with its own architecture and specifications that met with the requirement of current smartwatch SoC. This project obtained substantial results for power consumption lower than 25mW is achieved at 0.0112mW. A frequency higher than 40MHz is also achieved at 68MHz. Other than that, an architecture for smartwatch applications also has been determined with a variety of digital peripherals, off-chip peripherals and RISC-V core resulting into a comprehensive smartwatch SoC. Overall, this project contributes to the development of low power and high performance smartwatch SoC at a low cost value.

# Acknowledgment

The preferred spelling of the word “acknowledgment” in American English is without an “e” after the “g.” Use the singular heading even if you have many acknowledgments. Avoid expressions such as “One of us (S.B.A.) would like to thank ... .” Instead, write “F. A. Author thanks ... .” In most cases, sponsor and financial support acknowledgments are placed in the unnumbered footnote on the first page, not here.

References

1. J. U. Duncombe, “Infrared navigation—Part I: An assessment of feasibility,” *IEEE Trans. Electron Devices*, vol. ED-11, no. 1, pp. 34–39, Jan. 1959, doi: 10.1109/TED.2016.2628402.
2. E. P. Wigner, “Theory of traveling-wave optical laser,” *Phys. Rev*., vol. 134, pp. A635–A646, Dec. 1965.
3. P. Kopyt *et al., “*Electric properties of graphene-based conductive layers from DC up to terahertz range,” *IEEE THz Sci. Technol.,* to be published, doi: 10.1109/TTHZ.2016.2544142. *(Note: If a paper is still to be published, but is available in early access, please follow ref [5]).)*
4. R. Fardel, M. Nagel, F. Nuesch, T. Lippert, and A. Wokaun, “Fabrication of organic light emitting diode pixels by laser-assisted forward transfer,” *Appl. Phys. Lett.*, vol. 91, no. 6, Aug. 2007, Art. no. 061103.
5. D. Comite and N. Pierdicca, "Decorrelation of the near-specular land scattering in bistatic radar systems," *IEEE Trans. Geosci. Remote Sens.*, early access, doi: 10.1109/TGRS.2021.3072864. (*Note: This format is used for articles in early access. The doi must be included.)*
6. H. V. Habi and H. Messer, "Recurrent neural network for rain estimation using commercial microwave links," *IEEE Trans. Geosci. Remote Sens.*, vol. 59, no. 5, pp. 3672-3681, May 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9153027

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3. Philip B. Kurland and Ralph Lerner, eds., *The Founders’ Constitution.* Chicago, IL, USA: Univ. of Chicago Press, 1987, Accessed on: Feb. 28, 2010, [Online]. Available: http://press-pubs.uchicago.edu/founders/

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TABLE I

System of Smartwatches

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Vendor*** | ***Price (USD)*** | ***Released Date*** | ***Screen*** | ***Weight (g)*** | ***Width (mm)*** | ***Height (mm)*** | ***Thickness (mm)*** | ***Operating System*** | ***System Compatibility*** | ***Battery Capicity*** | ***Battery Lifetime*** |
| Watch Series 8 | Apple | 578 | Sep, 2022 | 1.9 inch Retina LTPO OLED | 51.5 | 38 | 45 | 10.7 | WatchOS | iOS | 308 | 36 |
| Watch Series 5 | Apple | 499 | Sep, 2019 | 1.57 inch LTPO OLED | 39.8 | 34 | 40 | 10.7 | WatchOS | iOS | 245 | 18 |
| Vantage V2 | Polar | 360 | Oct,2020 | 1.2 inch MIP | 52 | 47 | 47 | 13 | Proprietary | Android, iOS | 346 | 168 |
| 7 | Suunto | 342 | Jan, 2020 | 1.39 inch AMOLED | 70 | 24 | 50 | 15.3 | WearOS | Android, iOS | N.S. | 48 |
| Pixel | Google | 334 | Oct, 2022 | 1.2 inch AMOLED | 36 | 41 | 41 | 12.3 | ColorOS | Android, iOS | 294 | N.S. |
| Watch 3 Pro | Oppo | 288 | Aug, 2022 | 1.91 inch LTPO full-curve screen | 37.5 | 38.5 | 50.4 | 12.75 | ColorOS | Android, iOS | 550 | 336 |
| Sense | FitBit | 226 | Sep, 2020 | 1.58 inch AMOLED | N.S. | 40.4 | 40.4 | 12.4 | FitBit | Android, iOS | 266 | 168 |
| LEM15 | LEMFO | 222 | N.S., 2021 | 1.6 inch HD Round Screen | 73.5 | 50.7 | 50.7 | 16 | N.S. | Android, iOS | 900 | N.S. |
| Pace 2 | Coros | 220 | Aug, 2020 | 1.2 inch Memroy LCD | 29 | 42 | 42 | 11.7 | Proprietary | Android, iOS | N.S. | 480 |
| Watch 3 GS | Honor | 204 | Jan, 2022 | 1.43 inch AMOLED | 44 | 45.9 | 35.9 | 10.5 | Proprietary Lite | Android | 451 | 336 |
| GTS 4 | Amazfit | 199 | Oct, 2022 | 1.75 inch AMOLED | 27 | 36.5 | 42.7 | 9.9 | N.S. | Android, iOS | 300 | 384 |
| Forerunner 55 | Garmin | 199 | Jun, 2021 | 1.04 inch LCD MIP | 37 | 42 | 42 | 11.6 | Proprietary | Android, iOS | N.S. | 336 |
| Galaxy Watch Active 2 | Samsung | 195 | Sep,  2019 | 1.35 inch Super AMOLED | 42 | 44 | 44 | 10.9 | TizenOS | Android, iOS | 340 | 48 |
| Magic Watch 2 | Honor | 192 | Nov, 2019 | 1.39 inch OLED | 41 | 45.9 | 45.9 | 10.7 | Proprietary | Android | 455 | 336 |
| GT3 | Huawei | 190 | Oct, 2021 | 1.43 inch AMOLED | 42.6 | 45.9 | 45.9 | 11 | HarmonyOS | Android, iOS | 455 | 336 |
| Gen 6 | Fossil | 189 | Sep, 2021 | 1.28 inch AMOLED | 72.6 | 44 | 44 | 11.5 | WearOS | Android, iOS | 300 | N.S. |
| Gen 5 | Fossil | 189 | Aug, 2019 | 1.28 inch AMOLED | N.S. | 44 | 44 | 12 | WearOS | Android, iOS | 310 | N.S. |
| Galaxy Watch 5 | Samsung | 183 | Aug, 2022 | 1.4 inch Super AMOLED | 33.5 | 43.3 | 44.4 | 9.8 | WearOS | Android | 410 | 40 |

TABLE II

System of Smartwatches

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Vendor*** | ***Price (USD)*** | ***Released Date*** | ***Screen*** | ***Weight (g)*** | ***Width (mm)*** | ***Height (mm)*** | ***Thickness (mm)*** | ***Operating System*** | ***System Compatibility*** | ***Battery Capicity*** | ***Battery Lifetime*** |
| Watch | OnePlus | 159 | Mar,2021 | 1.39 inch AMOLED | 45 | 46.4 | 46.4 | 10.9 | Proprietary | Android | 402 | 336 |
| GT2 | Huawei | 155 | Sep, 2019 | 1.39 inch OLED | 41 | 45.9 | 45.9 | 10.7 | Proprieatary | Android, iOS | 455 | 336 |
| E3 | TicWatch | 150 | Jun, 2021 | 1.3 inch display 2.5D glass | 32 | 44 | 47 | 12.6 | WearOS | Android, iOS | 380 | N.S. |
| Moto watch 100 | Motorola | 90 | Dec, 2021 | 1.3 inch Circular LCD | 35 | 35.8 | 41.2 | 10.9 | MotoWatch | Andorid, iOS | 355 | 336 |
| Tank M2 | Kospet | 90 | Dec, 2022 | 1.85 inch IPS | 60 | 43.7 | 54 | 14 | N.S. | Android, iOS | 380 | 360 |
| Cross Fit 2 | North Edge | 79 | N.S., 2021 | 1.3 inch IPS LCD | 65 | 49 | 49 | 15 | Proprietary | Android, iOS | 320 | 120 |
| Watch 2 | Realme | 64 | Apr, 2021 | 1.4 inch IPS LCD | 38 | 25.8 | 35.7 | 12.2 | Proprietary | Android, iOS | 315 | 288 |
| KW10 PRO | KingWear | 60 | Feb, 2021 | 1.09 inch Round Touch Screen | N.S. | 42 | 42 | 11 | N.S. | Android, iOS | 180 | N.S. |
| Mi Watch Lite | Xiaomi | 59 | Dec, 2020 | 1.4 inch LCD display | 35 | 35 | 41 | 11.9 | Proprietary | Android, iOS | 230 | 216 |
| Mi Watch 2 Lite | Xiaomi | 55 | Nov, 2021 | 1.55 inch TFT LCD | 35 | 35.8 | 41.2 | 10.9 | Proprietary | Android, iOS | 262 | 240 |
| C22 | Bozlun | 50 | N.S. | 1.6 inch LCD | 60 | 46 | 46 | 13 | N.S. | Android, iOS | 400 | N.S. |
| BoAT Blaze | boAT | 49 | Feb, 2022 | 1.75 inch AMOLED | 43.8 | 26 | 26 | 32 | N.S. | Android, iOS | 220 | 168 |
| Beyond 2 | Zeblaze | 49 | N.S., 2022 | 1.78 inch AMOLED | 42.4 | 37 | 45 | 10.5 | N.S. | Android, iOS | 180 | 336 |
| Watch Foom S | Aolon | 47 | N.S. | 1.8 inch IPS HD Color Screen | 57 | 37.9 | 46.4 | 11.8 | N.S. | Android, iOS | 260 | 168 |
| ZL02 | Bozlun | 46 | N.S., 2021 | 1.28 inch IPS | 45 | 45.5 | 45.5 | 10 | N.S. | Android, iOS | 220 | 168 |
| Amazfit ARC | Amazfit | 44 | Oct, 2016 | 0.42 inch OLED | 20 | 19 | 11 | 245 | Proprietary | Android, iOS | 70 | 480 |
| Watch 3 | Realme | 43 | Aug, 2022 | 1.8 inch IPS LCD | 40 | 37 | 45 | 11.5 | Proprietary | Android, iOS | 340 | 168 |
| P80S | Bozliun | 43 | N.S. | 1.6 inch IPS | 50 | 36 | 42 | 11 | N.S. | Android, iOS | 180 | 120 |
| CS2 | Doogee | 42 | May, 2021 | 1.69 inch LCD | 35 | 36.9 | 43.8 | 10.5 | N.S. | Android, iOS | 300 | 360 |
| S2 Pro | Lenovo | 40 | Apr, 2021 | 1.69 inch IPS Full Touch | 40.3 | 76 | 165.2 | 9.2 | N.S. | Android, iOS | 250 | 360 |
| P10 | Colmi | 40 | Feb, 2021 | 1.3 inch IPS | 33 | 41 | 46 | 11 | N.S. | Android, iOS | 170 | 168 |

TABLE III

System of Smartwatches

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Vendor*** | ***Price (USD)*** | ***Released Date*** | ***Screen*** | ***Weight (g)*** | ***Width (mm)*** | ***Height (mm)*** | ***Thickness (mm)*** | ***Operating System*** | ***System Compatibility*** | ***Battery Capicity*** | ***Battery Lifetime*** |
| ADV S2 | Aolon | 37 | N.S. | 1.92 inch IPS HD Color | 45 | 36 | 44 | 12 | N.S. | Android, iOS | 260 | 120 |
| WT2105 | Maimo | 36 | N.S. | 1.69 inch TFT LCD Screen | 24 | 37 | 43.75 | 11 | N.S | Android, iOS | 300 | 504 |
| GST | Haylou | 32 | Dec, 2021 | 1.69 inch TFT display | 42 | 38.7 | 49.9 | 11.7 | N.S. | Android, iOS | N.S. | 216 |
| C21 | SKMEI | 32 | N.S., 2019 | 1.32 inch TFT | 60 | 46.5 | 46.5 | 13 | N.S. | Android, iOS | 300 | 120 |
| LS02 | Aukey | 32 | Aug, 2021 | 1.4 inch TFT LCD | 38 | 36 | 48 | 12 | N.S. | Android, iOS | 260 | 480 |
| C5 | Cubot | 32 | Aug, 2021 | 1.7 inch TFT LCD | 40 | 37.2 | 43 | 12 | N.S. | Android, iOS | 260 | 168 |
| KU1 S | Kumi | 30 | Oct, 2020 | 1.54 inch IPS Color Screen | 33 | 30 | 40 | 11.2 | N.S. | Android, iOS | 210 | 360 |
| H40 | SKMEI | 30 | N.S. | 1.3 inch Colorful LCD | N.S. | 45 | 45 | 11 | N.S. | Android, iOS | 290 | 168 |
| DT8 Ultra + | DT No.1 | 30 | Oct, 2022 | 2.1 inch TFT | 36 | 43 | 49 | 11.5 | N.S. | Android, iOS | 280 | 120 |
| P45 | Colmi | 30 | Apr, 2022 | 1.81 inch IPS | 50 | 38 | 43 | 13.52 | N.S. | Android, iOS | 260 | 144 |
| KU6 | Kumi | 30 | Nov, 2022 | 1.91 inch HD | 41 | 37 | 47 | 11.3 | N.S. | Android, iOS | 300 | 168 |
| 15 Ultra | iwo | 25 | Sep, 2022 | 2.02 inch IPS | N.S. | 40 | 45 | 10.2 | N.S. | Android, iOS | 200 | 168 |

TABLE IV

Board of Smartwatches

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Vendor*** | ***Price (USD)*** | ***Released Date*** | ***Microntroller SoC*** | ***Bit*** | ***Off-Chip RAM*** | ***Off-Chip Storage*** | ***On-board Sensors*** | ***On-board RF*** |
| Watch Series 8 | Apple | 578 | Sep, 2022 | Apple S8 Dual Core | 64 | 1GB | 32GB | Accelerometer, Ambient Light, Gyroscope, ECG Heart Rate, Altimeter Magnetometer, Blood Oxygen, Barometer, Temperature | Bluetooth, NFC, Wi-Fi, GLONASS, Galileo, QZSS, BDS |
| Watch Series 5 | Apple | 499 | Sep, 2019 | Apple S5 Dual Core | 64 | 1GB | 32GB | Accelerometer, Gyroscope, Heart Rate, Magnetometer, Barometer, Altimeter, ECG | Bluetooth, GPS, GLONASS, Galileo, QZSS, Wi-Fi |
| Vantage V2 | Polar | 360 | Oct,2020 | N.S. | N.S. | 0.64MB | 32MB | Heart Rate, Barometer, Magnetometer, Accelerometer, Ambient Light | Bluetooth, GPS, Galileo, GLONASS, QZSS |
| 7 | Suunto | 342 | Jan, 2020 | Wear 3100 | N.S. | 1GB | 8GB | Accelerometer, Altimeter, Ambient Light, Barometer, Magnetometer, Gyroscope, Heart Rate | Bluetooth, BEIDOU, GLONASS, GPS, QZSS, Wi-Fi |

TABLE V

Board of Smartwatches

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Vendor*** | ***Price (USD)*** | ***Released Date*** | ***Microntroller SoC*** | ***Bit*** | ***Off-Chip RAM*** | ***Off-Chip Storage*** | ***On-board Sensors*** | ***On-board RF*** |
| Pixel | Google | 334 | Oct, 2022 | Exynos 9110 SoC Cortex M33 co-processor | N.S. | 2GB | 32GB | Accelerometer, Gyrospcope, Heart Rate, Altimeter, Magnetometer, SP02 | 4G LTE, Bluetooth, Wi-Fi, NFC, GPS, GLONASS, BEIDOU, Galileo |
| Watch 3 Pro | Oppo | 288 | Aug, 2022 | Snapdragon W5+ Gen 1 & Apollo 4 Plus | N.S. | 1GB | 32GB | Accelerometer, Gyroscope, Geomagnetic Heart rate, SP02, ECG, Light, Barometric | Bluetooth, LTE, GPS, GLONASS, BDS, Galileoi, QZSS |
| Sense | FitBit | 226 | Sep, 2020 | FBT18SW | N.S. | N.S. | 4GB | Heart Rate, SPO2 Gyroscope, Altimeter, Accelerometer, Temperature, Ambient Light | Bluetooth, GPS, GLONASS |
| LEM15 | LEMFO | 222 | N.S., 2021 | MT6762 | N.S. | 4GB | 128GB | Heart Rate, Pedometer | Bluetooth, WiFi, GPS, Cellular Network |
| Pace 2 | Coros | 220 | Aug, 2020 | N.S. | N.S. | N.S. | N.S. | Heart Rate, Barometer, Altimeter, Accelerometer, Gyroscope, Magnetometer, Thermometer | Bluetooth, GPS, Galileo, GLONASS, BEIDOU |
| Watch 3 GS | Honor | 204 | Jan, 2022 | Apollo 4 | N.S. | 32MB | 4GB | Accelerometer, Gyroscope, Heart Rate, Barometer, Magnetometer, SPO2 | Bluetooth, GPS, GLONASS, BDS, Galileo, QZSS |
| GTS 4 | Amazfit | 199 | Oct, 2022 | Exynos 9000 | N.S. | 1GB | 3GB | Heart Rate, SP02, Accelerometer, Geomagnetic, Ambient light | Bluetooth, WLAN, NFC  GPS |
| Forerunner 55 | Garmin | 199 | Jun, 2021 | N.S. | N.S. | N.S. | N.S. | Accelerometer, Heart Rate | Bluetooth, ANT+, GPS, GLONASS, Galileo |
| Galaxy Watch Active 2 | Samsung | 195 | Sep,  2019 | Samsung Exynos 9110 | N.S. | 1.5GB | 4GB | Accelerometer, Gyroscope, Heart Rate, Vibration, Barometer, ECG | Bluetooth, NFC, Wi-Fi, GPS, GLONASS, Galileo, BDS |
| Magic Watch 2 | Honor | 192 | Nov, 2019 | Huawei Kirin A1 | N.S. | 32MB | 4GB | Accelerometer, Gyroscope, Heart Rate, Barometer, Magnetometer | Bluetooth, GPS, GLONASS, Galileo |
| GT3 | Huawei | 190 | Oct, 2021 | N.S. | N.S. | 32MB | 4GB | Accelerometer, Gyroscope, Geomagnetic, Optical Heart Rate, Barometric, Temperature | Bluetooth, GPS, GLONASS, Galileo, BDS, QZSS |
| Gen 6 | Fossil | 189 | Sep, 2021 | Qualcomm Snapdragon Wear 4100+ | N.S. | 1GB | 8GB | Accelerometer, Altimeter, Ambient Light, Compass, Gyroscope, Infra-Red, Heart Rate , SPO2 | Bluetooth 5.0, GPS, NFC, Wi-Fi |
| Gen 5 | Fossil | 189 | Aug, 2019 | Qualcomm Snapdragon Wear 3100 | N.S. | 1GB | 8GB | Accelerometer, Gyroscope, Heart Rate Light, Magnetometer Vibration, Infra-red | Bluetooth, GPS NFC, Wi-Fi |

TABLE VI

Board of Smartwatches

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Vendor*** | ***Price (USD)*** | ***Released Date*** | ***Microntroller SoC*** | ***Bit*** | ***Off-Chip RAM*** | ***Off-Chip Storage*** | ***On-board Sensors*** | ***On-board RF*** |
| Galaxy Watch 5 | Samsung | 183 | Aug, 2022 | Exynos W920 | N.S. | 1.5GB | 16GB | Accelerometer, Barometer, Bioelectrical, Gyroscope, Geomagnetic, Light, Electrical, and Optical Heart Rate | Bluetooth, GPS, GLONASS, Galileo, BDS, NFC, Wi-Fi |
| Watch | OnePlus | 159 | Mar,2021 | ST32, Apollo 3 | N.S. | 1GB | 4GB | Accelerometer, Gyroscope Geomagnetic Optical heart rate, SPO2, Ambient light, Barometric, Capacitive | Bluetooth, GPS, GLONASS, Galileo, BEIDOU |
| GT2 | Huawei | 155 | Sep, 2019 | Huawei Kirin A1 | N.S. | 32MB | 4GB | Accelerometer, Gyroscope, Geomagnetic, Optical heart rate, Ambient light, Barometric, Capacitive | Bluetooth, GPS, GLONASS, Galileo |
| E3 | TicWatch | 150 | Jun, 2021 | Snapdragon 4100 Platform Mobvoi Dual Processor | N.S. | 1GB | 8GB | Accelerometer, Gyroscope, Heart Rate, SPO2 | Bluetooth, Wi-Fi, GPS, GLONASS BeiDou, NFC |
| Moto watch 100 | Motorola | 90 | Dec, 2021 | N.S. | N.S. | N.S. | N.S. | Accelerometer, Gyroscope, Heart Rate, SPO2, Ambient Light | Bluetooth, GPS, GLONASS |
| Tank M2 | Kospet | 90 | Dec, 2022 | RTL8763EW | 32 | 64kB | 128MB | Heart Rate, Pedometer, Accelerometer | Bluetooth |
| Cross Fit 2 | North Edge | 79 | N.S., 2021 | MTK2503 | N.S. | 32MB | 120MB | Heart Rate, Barometer, Altimeter, Magnetometer | Bluetooth, GPS |
| Watch 2 | Realme | 64 | Apr, 2021 | N.S. | N.S. | N.S. | N.S. | Heart Rate, SPO2, Accelerometer | Bluetooth |
| KW10 PRO | KingWear | 60 | Feb, 2021 | NRF52832 | 32 | 64kB | 512kB | Heart rate, SPO2, Accelerometer | Bluetooth |
| Mi Watch Lite | Xiaomi | 59 | Dec, 2020 | N.S. | N.S. | N.S. | N.S. | Accelerometer, Gyropscope, Heart Rate Magnetometer, Vibration Barometer | Bluetooth, GPS, GLONASS |
| Mi Watch 2 Lite | Xiaomi | 55 | Nov, 2021 | Ambiq Apollo 3.5 | 32 | N.S. | N.S. | Optical Heart Rate, Accelerometer,Gyroscope, Magnetometer | Bluetooth, GPS, GLONASS, Galileo, BDS |
| C22 | Bozlun | 50 | N.S. | ATS3085 | 32 | 1GB | 4GB | Heart Rate, SPO2 | Bluetooth |
| BoAT Blaze | boAT | 49 | Feb, 2022 | Apollo Blue Plus 3 | 32 | N.S. | N.S. | Accelerometer, Heart Rate, SP02 | Bluetooth |
| Beyond 2 | Zeblaze | 49 | N.S., 2022 | DA14695 | 32 | 128MB | N.S. | Heart Rate, SPO2 Accelerometer, Proximity | Bluetooth, GPS, GLONASS, Galileo, BeiDou |
| Watch Foom S | Aolon | 47 | N.S. | GR5515 Ultra-low Power AC6963A | 32 | 256kB | 64MB | Heart Rate, Accelerometer | Bluetooth |
| ZL02 | Bozlun | 46 | N.S., 2021 | DA14695 | 32 | N.S. | N.S. | Heart Rate, Accelerometer | Bluetooth |
| Amazfit ARC | Amazfit | 44 | Oct, 2016 | DA14681 | 32 | 128kB | N.S. | Accelerometer, Pedometer, Heart Rate | Bluetooth |
| Watch 3 | Realme | 43 | Aug, 2022 | N.S. | N.S. | N.S. | N.S. | Optical Heart Rate, SPO2, Accelerometer | Bluetooth |
| P80S | Bozliun | 43 | N.S. | HS6621 | 32 | N.S. | 64MB | Heart Rate, Accelerometer | Bluetooth |
| CS2 | Doogee | 42 | May, 2021 | RTL8762C | 32 | N.S. | 128MB | Accelerometer, Heart Rate | Bluetooth |
| S2 Pro | Lenovo | 40 | Apr, 2021 | N.S. | N.S. | N.S. | N.S. | Accelerometer, Heart Rate, Temperature | Bluetooth, GLONASS, BeiDou, Galileo |

TABLE VII

Board of Smartwatches

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Vendor*** | ***Price (USD)*** | ***Released Date*** | ***Microntroller SoC*** | ***Bit*** | ***Off-Chip RAM*** | ***Off-Chip Storage*** | ***On-board Sensors*** | ***On-board RF*** |
| P10 | Colmi | 40 | Feb, 2021 | RTL8762C | 32 | N.S. | N.S. | Accelerometer, Heart Rate, Gyroscope, Optical Heart, SP02 | Bluetooth |
| ADV S2 | Aolon | 37 | N.S. | AC6954 | 32 | N.S. | N.S. | Heart Rate, Accelerometer | Bluetooth, NFC |
| WT2105 | Maimo | 36 | N.S. | N.S. | N.S. | N.S. | N.S. | Accelerometer, Heart Rate | Bluetooth |
| GST | Haylou | 32 | Dec, 2021 | RTL8762C | 32 | N.S. | N.S. | Heart Rate, Motion, SPO2 | Bluetooth |
| C21 | SKMEI | 32 | N.S., 2019 | RTL8762DK | 32 | N.S. | N.S. | Heart Rate, Accelerometer | Blueetoh |
| LS02 | Aukey | 32 | Aug, 2021 | N.S. | N.S. | N.S. | N.S. | Heart Rate, Accelerometer | Bluetooth |
| C5 | Cubot | 32 | Aug, 2021 | RTL8752C | 32 | N.S. | N.S. | Heart Rate, Gyroscope Accelerometer | Bluetooth |
| KU1 S | Kumi | 30 | Oct, 2020 | RTL8762C | 32 | N.S. | N.S. | Heart Rate, Accelerometer | Bluetooth |
| H40 | SKMEI | 30 | N.S. | RTL8762CW | 32 | 128kB | N.S. | Heart Rate | Bluetooth |
| DT8 Ultra + | DT No.1 | 30 | Oct, 2022 | RTL8762D | 32 | N.S. | N.S. | Heart Rate Accelerometer, SPO2, Temperature | Bluetooth, GPS, NFC |
| P45 | Colmi | 30 | Apr, 2022 | GR5515 | 32 | 128MB | N.S. | Heart Rate, Accelerometer | Bluetooth |
| KU6 | Kumi | 30 | Nov, 2022 | RTL8763EW | 32 | 64MB | 128MB | Heart Rate, Accelerometer | Bluetooth, NFC |
| 15 Ultra | iwo | 25 | Sep, 2022 | HS6621 | 32 | N.S. | N.S. | Heart Rate, SPO2, Accelerometer | Bluetooth, NFC |

TABLE VIII

Specifications of Smartwatch SoCs

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Price (USD)*** | ***Bits*** | ***Core*** | ***Core Clock (MHz)*** | ***RAM(kB)*** | ***ROM (kB)*** | ***Flash*** | ***Cache (kB)*** | ***Power (mW)*** |
| nrf52832 | 65 | 32 | 1 | 64 | 64 | N.S. | 512kB | N.S. | 6.3104 |
| DA14695 | 60 | 32 | N.S | 96 | 512 | 128 | N.S. | 16 | 10.54 |
| ATS3085 | 50 | 32 | 1 | 128 | 481 | N.S. | 2MB | N.S. | N.S. |
| Apollo 3 Blue Plus | 49 | 32 | 1 | 96 | 768 | N.S. | 2MB | 16 | 6.9077 |
| RTL8762C | 40 | 32 | 1 | 40 | 160 | N.S. | 8MB | 16 | 20.34 |
| DA14681 | 36 | 32 | 1 | 96 | 128 | 128 | N.S. | 16 | 10.54 |
| RTL8762D | 35 | 32 | 1 | 90 | 192 | 256 | 32MB | 16 | 25.074 |
| HS6621 | 35 | 32 | 1 | 128 | 256 | 256 | 8MB | N.S. | 10.8 |
| GR5515 | 30 | 32 | 1 | 64 | 256 | N.S. | 1MB | N.S. | 3.264 |

TABLE IX

Digital Peripherals of Smartwatch SoCs

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Name*** | ***Price (USD)*** | ***GPIO*** | ***I2C*** | ***I2S*** | ***UART*** | ***SPI*** | ***PWM*** | ***PDM*** | ***Watchdog Timer*** | ***Timer*** | ***ADC*** |
| nrf52832 | 65 | 32 | 2 | 1 | 1 | 3 | 3 | 1 | N.S. | 3 | N.S. |
| DA14695 | 60 | 55 | 2 | 1 | 3 | 2 | N.S. | 1 | 1 | 5 | N.S. |
| ATS3085 | 50 | N.S. | 4 | N.S. | 3 | 6 | 9 | N.S. | 1 | 1 | 1 |
| Apollo 3 Blue Plus | 49 | 74 | 7 | 1 | 2 | 7 | 8 | 1 | 1 | 3 | 1 |
| RTL8762C | 40 | 38 | 2 | 1 | 2 | 2 | 8 | N.S. | N.S. | 1 | 1 |
| DA14681 | 36 | 37 | 2 | 1 | 2 | 2 | N.S | 1 | 1 | 3 | 1 |
| RTL8762D | 35 | 40 | 2 | 1 | 2 | 2 | 8 | 2 | N.S. | 1 | 1 |
| HS6621 | 35 | 30 | 1 | 1 | 1 | 1 | 1 | N.S. | 1 | 1 | 1 |
| GR5515 | 30 | 39 | 2 | 2 | 2 | 2 | 1 | N.S. | 2 | 1 | 1 |

|  |  |  |  |
| --- | --- | --- | --- |
|  | Smartwatch | | |
|  | Min. | Avg. | Max. |
| Price (USD) | 25 | 130 | 578 |
| Bit | 32 | - | 64 |
| Off-Chip RAM (kB) | 64 | 695,760 | 4,000,000 |
| Off-Chip ROM (kB) | 32,000 | 12,600,000 | 128,000,000 |
| Battery Capacity (mAh) | 70 | 313.17 | 900 |
| Battery Lifetime (h) | 18 | 243.86 | 504 |
| Volume (mm3) | 11,236.93 | 23,868.60 | 115,507.84 |
| Weight (g) | 20 | 42.76 | 73.5 |

1. This paragraph of the first footnote will contain the date on which you submitted your paper for review, which is populated by IEEE. It is IEEE style to display support information, including sponsor and financial support acknowledgment, here and not in an acknowledgment section at the end of the article. [↑](#footnote-ref-0)
2. It is recommended that footnotes be avoided (except for the unnumbered footnote with the receipt date on the first page). Instead, try to integrate the footnote information into the text. [↑](#footnote-ref-1)