WiP: Towards a Secure SECP256K1 for Crypto Wallets: Hardware Architecture and Implementation

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Abstract—The SECP256K1 elliptic curve algorithm is fundamental in cryptocurrency wallets for generating secure public keys from private keys, thereby ensuring the protection and ownership of blockchain-based digital assets. However, the literature highlights several successful side-channel attacks on hardware wallets that exploit SECP256K1 to extract private keys. This work proposes a novel hardware architecture for SECP256K1, optimized for side-channel attack resistance and efficient resource utilization. The architecture incorporates complete addition formulas, temporary registers, and parallel processing techniques, making elliptic curve point addition and doubling operations indistinguishable. Implementation results demonstrate an average reduction of 45% in LUT usage compared to similar works, emphasizing the design's resource efficiency.

Index Terms—component, formatting, style, styling, insert

I. INTRODUCTION

Cryptocurrency (crypto) wallets are vital in ensuring the security of digital assets. They generate, store, and manage public and private cryptographic keys. While public keys are openly accessible, the secrecy of private keys is paramount. They serve as proof of ownership, granting full access to associated crypto assets [1]. Therefore, a compromised private key can result in significant losses. The wallets extensively use cryptographic functions to secure the keys. For example, Ethereum and Bitcoin wallets use the SECP256K1 hash function to generate public keys from private keys. However, studies have demonstrated the extraction of private keys from crypto wallets using side channel analysiss (SCAs) attack, where attackers target the SECKP256K1 [2]. Therefore, this work presents a hardware architecture and implementation for SECP256K1, specifically designed to withstand SCA attacks.

Elliptic Curve Cryptography (ECC):: SECP256K1 is a specific elliptic curve (EC) in the elliptic curve cryptography (ECC) ecosystem. ECC is pivotal in public key cryptography, and it operates on an EC defined over a finite Galois field (GF) [3]. It is used to generate and verify digital signatures and authenticate information. Moreover, ECC utilizes shorter cryptographic keys than RSA while providing the same level of security [4]. Hence, it is attractive for applications with limited resources such as crypto hardware wallets.

In ECC, two primary finite field types are prevalent: prime fields, denoted as $GF(\mathbb{F}_p)$, where p is a large prime number and binary extension fields, denoted as $GF(\mathbb{F}_{2^n})$, where 2^n is the field's size, n is a positive integer [3]. The EC is defined

as $y^2 + xy = x^3 + ax + b$, where x and y are coordinates on the EC, and a and b are constants that define the curve. After applying a linear transformation to the variables, the EC equation is reformulated in the standard short Weierstrass form to $y^2 = x^3 + ax + b$ [5].

Three main processes are carried out on the EC to compute public keys. These are elliptic curve point addition (ECPA), elliptic curve point doubling (ECPD), and elliptic curve point multiplication (ECPM) [6]. Fig. 1 (A) shows the ECPA process defined by $\mathbf{R} = \mathbf{P} + \mathbf{Q}$. The figure illustrates the addition of two points, $\mathbf{P} = (x_0, y_0)$ and $\mathbf{Q} = (x_1, y_1)$ on the EC. As shown, adding \mathbf{P} and \mathbf{Q} is equivalent to drawing a straight line through points \mathbf{P} and \mathbf{Q} , which intersect with the curve at point $-\mathbf{R}$. Reflecting the point of intersection by the x-axis results in point \mathbf{R} , the ECPA solution.

Conversely, ECPD is the addition of a point on the EC by itself. Fig. 1 (B) depicts the ECPD process defined by $\mathbf{R}=2\mathbf{P}$. The figure illustrates the addition of a point, $\mathbf{P}=(x_0,y_0)$ with itself on the EC. As shown, doubling \mathbf{P} is equivalent to drawing a line tangent to the EC on point \mathbf{P} , which intersects with the curve at point $-\mathbf{R}$. Reflecting the point of intersection by the x-axis results in point \mathbf{R} , the ECPD solution.

The scalar ECPM process uses the ECPA and the ECPD inside an algorithm, for instance, inside the Montgomery Ladder algorithm [3]. ECPM is the main process used to compute a public key given a private key, and it is defined as $\mathbf{R} = k \cdot \mathbf{P}$. It is the sum of k copies of \mathbf{P} , such that:

$$\mathbf{R} = k \cdot \mathbf{P} = \sum_{i=1}^{k} \mathbf{P},\tag{1}$$

where R and P are points on the curve and k is a long binary number. SECP256K1 is an EC whose a and b parameters are 0 and 7, respectively [7]. Moreover, Table I shows other curve parameters. G is the generator point. It is a specific point on the EC used as the basis for generating all other points on the curve through ECPM. G is formulated as $G = x04 \parallel x \parallel y$, where, x04 is a format identifier and x and y are coordinates from a point on the EC.

SCA on SECP256K1:: In protocols that utilize ECC, k is usually considered a private key. Hence, a successful attack correctly derives k via unauthorized means. For example, an SCA attack can exploit the current drawn or electromagnetic

TABLE I PARAMETERS FOR THE SECP256K1 EC

waves emitted by an ECC device while processing k. The attack relies on the variations in power consumption when bit value 1 or 0 of k is being processed (i.e. k_i where i is the index).

The Montgomery Ladder algorithm depicted in Alg. 1 is popularly used to calculate ECPM [3]. The algorithm details the bitwise processing of the secret key k from most significant bit (MSB) to least significant bit (LSB). Montgomery Larder is balanced, meaning that the sequence of mathematical operations is independent of the private key. Hence, the literature considers the algorithm safe against simple SCA attacks [4].

Nevertheless, the algorithm contains inconsistencies that may make it susceptible to differential power analysis (DPA) and timing attacks. The ECPD in each branch of the *if* statement is performed on different registers. When m_i is 1 ECPD is performed on R_1 . Conversely, when m_i is 0 ECPD is performed on R_0 . These differences create a power consumption pattern or execution time discrepancy, where different registers, memory locations, and data paths are utilized. Such patterns can be exploited by attackers to extract m [4]. Moreover, the conventional Weierstrass EC addition operation contains branching when computing ECPA, ECPD, or a point at infinity. The branching can cause timing variability which can be exploited to reveal the secret key [7].

Various works in literature have proposed ways to protect the Montgomery larder algorithm against SCA attacks. For example, the work in [8] proposed a method to randomize the sequence of writing Q_0 and Q_1 inside the loop. However, branches still access different registers, making the risk of SCA attacks persistent.

Algorithm 1 Montgomery Ladder. Adapted from [9]

```
Input: P, k = k_l k_{l-1} \dots k_0, with k_l = 1
Q_0 \leftarrow P; \ Q_1 \leftarrow 2P
for i = (l-2) downto 0 do

if k_i = 1 then Q_0 \leftarrow Q_0 + Q_1; \ Q_1 \leftarrow 2Q_1
else Q_1 \leftarrow Q_0 + Q_1; \ Q_0 \leftarrow 2Q_0
end if
end for
Output: Q = kP
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Contribution and Organization:: This work proposes a hardware architecture and implementation of a SECP256K1 module for crypto wallets that are secure against SCA attacks while utilizing minimum resources hence adhering to the industry standard for small, compact, and portable wallets. The module employs temporary registers and parallel processing to

Algorithm 2 Point addition equations. Taken from [7]

Input: $P = (X_1, Y_1, Z_1), Q = (X_2, Y_2, Z_2)$ on $E : Y^2Z = X^3 + bZ^3$ and $b_3 = 3 \cdot b$. **Output:** $(X_3, Y_3, Z_3) = P + Q$;

 $t_0 \leftarrow X_1 \cdot X_2$ $X_3 \leftarrow t_1 + t_2$ $t_1 \leftarrow t_1 - t_2$ $t_1 \leftarrow Y_1 \cdot Y_2$ $t_4 \leftarrow t_4 - X_3$ $Y_3 \leftarrow b_3 \cdot Y_3$ $t_2 \leftarrow Z_1 \cdot Z_2$ $X_3 \leftarrow X_1 + Z_1$ $X_3 \leftarrow t_4 \cdot Y_3$ $t_3 \leftarrow X_1 + Y_1$ $Y_3 \leftarrow X_2 + Z_2$ $t_2 \leftarrow t_3 \cdot t_1$ $t_4 \leftarrow X_2 + Y_2$ $X_3 \leftarrow X_3 \cdot Y_3$ $X_3 \leftarrow t_2 - X_3$ $Y_3 \leftarrow t_0 + t_2$ $Y_3 \leftarrow Y_3 \cdot t_0$ $t_3 \leftarrow t_3 \cdot t_4$ $t_4 \leftarrow t_0 + t_1$ $Y_3 \leftarrow X_3 - Y_3$ $t_1 \leftarrow t_1 \cdot Z_3$ $t_3 \leftarrow t_3 - t_4$ $X_3 \leftarrow t_0 + t_0$ $Y_3 \leftarrow t_1 + Y_3$ $t_4 \leftarrow Y_1 + Z_1$ $t_0 \leftarrow t_0 \cdot t_3$ $t_0 \leftarrow X_3 + t_0$ $Z_3 \leftarrow Z_3 \cdot t_4$ $X_3 \leftarrow Y_2 + Z_2$ $t_2 \leftarrow b_3 \cdot t_2$ $t_4 \leftarrow t_4 \cdot X_3$ $Z_3 \leftarrow t_1 + t_2$ $Z_3 \leftarrow Z_3 + t_0$

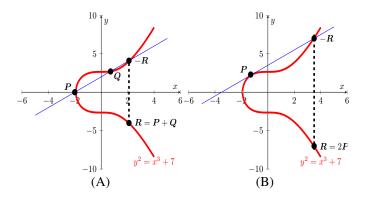


Fig. 1. ECPA (A) and ECPD (B) on EC. Adapted from [5].

prevent variations during ECPM. Moreover, the complete addition formulas are used to prevent timing variability [7]. The remainder of this work is structured as follows. Section II describes the hardware architecture of the proposed SECP256K1 function. Section III discusses the implementation results and Section IV provides the conclusion.

II. HARDWARE ARCHITECTURE OF THE SECP256K1

SECP256K1 executes modular arithmetic operations, including addition, subtraction, multiplication, and division in an affine coordinate system, i.e., $GF(\mathbb{F}_p)$ where $\mathbb{F}_p \in (x,y)$ [6]. However, modular inversion/division is the most expensive in complexity, area, and execution time [10], [11]. Nevertheless, transforming the coordinates from affine to projective reduces the number of modular division operations performed by SECP256K1 (i.e., $GF(\mathbb{F}_p)$ where $\mathbb{F}_p \in (x, y, z)$) [6]. Therefore, Alg. 2 depicts a set of equations used to compute the complete ECPA in the projective coordinate system over prime-order elliptic curves. The equations thwart SCA attacks by removing the branching inherent to the addition operation of the short Weierstrass ECs. The branching causes timing variability that could leak secret data [7]. This work employs the equations inside the Montgomery Larder algorithm to perform SECP256K1 ECPM in projective coordinates.

However, SECP256K1 must perform one final modular division to return the final results to affine coordinates, i.e $(x,y,z)\Rightarrow (xz^{-1},yz^{-1})$. SECP256K1 utilizes the binary inversion algorithm (BIA) to compute the modular division. The algorithm is based on the Extended Euclidean algorithm (EEA) which calculates the multiplicative inverse of an integer $z\in\mathbb{F}_p$ by calculating two variables R and q that satisfy $zR+pq=\gcd(z,p)=1$, where \gcd is a function used to calculate the greatest common divisor of two numbers [11]. Hence, the proposed architecture comprises two main parts, SECP256K1 ECPM and BIA.

A. Architecture of SECP256K1 ECPM

ECPM is accomplished by employing ECPA and ECPD in the Montgomery Ladder algorithm as shown in Alg. 1. Moreover, ECPD is computed using ECPA where the two points are similar (i.e., R = P + P = 2P). Therefore, we commence by designing the ECPA module. This work uses the equations in Alg. 2 to design ECPA.

All operations in Alg. 2 are modulo \mathbb{P} , where \mathbb{P} is a specific prime number chosen for SECP256K1 shown in Table I. Therefore, we first design a modular arithmetic logic unit (MALU) to perform modular addition, subtraction, and multiplication. A shift-and-add algorithm is utilized to perform the modular operations [12]. Subsequently, the proposed Montgomery Ladder algorithm employing the ECPM architecture is shown in Alg. 3. A temporary register file R_t is added to prevent variability and maintain uniformity in both branches when processing $k_i = 1$ and $k_i = 0$. R_t is loaded with R_0 when $k_i = 1$ and R_1 when $k_i = 0$. Moreover, registers R_0 , R_1 , and R_t are loaded in parallel. This helps prevent further variations where a uniform control structure that does not depend on the order of operations is created [4].

Fig. 2 shows the proposed hardware architecture for the Montgomery Ladder algorithm in Alg. 3 implementing the SECP256K1 hash function. Moreover, the doted blue modules are the ECPA hardware architecture implementing the equations in Alg. 2. The Montgomery Ladder architecture utilizes two ECPA modules that run in parallel. A Controller (Cntl) takes the bit values k_i of the private key and controls all the select and enable signals for multiplexers and registers respectively. Moreover, the solid green module shows the binary inversion algorithm (BIA) architecture.

Algorithm 3 Montgomery Ladder algorithm with temporary registers. Adapted from [9]

```
Input: P \in (x, y, z), k = (k_{t-1}, \cdots, k_0) with k_{t-1} = 1

1: R_0 \leftarrow P; R_1 \leftarrow 2P

2: for i = t - 2 : 0 do

3: if k_i = 1 then R_0 \leftarrow R_0 + R_1; R_1 \leftarrow 2R_1; R_t \leftarrow 2R_0

4: else R_1 \leftarrow R_0 + R_1; R_0 \leftarrow 2R_0; R_t \leftarrow 2R_1

5: end if

6: end for

Output: \hat{R} = nP
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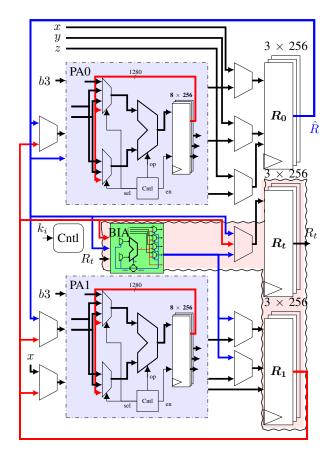


Fig. 2. The proposed hardware architecture of SECP256K1 hash function.

B. Architecture of Binary Inversion

The output of the Montgomery Ladder \hat{R} in Fig. 2 is in projective coordinate form (i.e., $\hat{R} = (x_0, y_0 z_0) \in GF(p)$). Therefore, \hat{R} must be converted to affine coordinates to represent a public key in a crypto wallet. The point in affine coordinates is computed by calculating the modular multiplicative inverse of the value in the z-axis and multiplying it with the x- and y-axis values of \hat{R} , i.e, $(x_0 r, y_0 r) \Rightarrow (x_1, y_1)$, where $r = z^{-1} \mod$ p. This work employs the binary inversion algorithm (BIA) to calculate r [11]. The algorithm uses additions, subtractions, and shifting operations to compute the multiplicative inverse. Due to its expensive resource consumption, this is the only modular division performed in SECP256K1 implementation using projective coordinates. The solid green module in Fig. 2 depicts the proposed architecture of BIA. The architecture also reuses registers R_1 and R_t shown by the rugged red region. After execution, the affine coordinates (i.e, (x, y)) are stored in R_t . Crypto wallets use the coordinate as a public key K_{pub} .

III. FPGA IMPLEMENTATION RESULTS AND DISCUSSION

A Xilinx ZCU104 and an Artix-7 field programmable gate array (FPGA) boards were used to implement the proposed SECP256K1 architecture. Moreover, Vivado 2022.2 was used for simulation and a reference software implementation was used to verify the output. The comparison in Table II evaluates the proposed implementation against state-of-the-art solutions.

TABLE II
COMPARING IMPLEMENTATION RESULTS OF THE SECP256K1 ALGORITHM.

Work	Platform		Area			Frequency	Latency		Throughput ^a
		kLUT	DSP	RAM (kbits)	Registers	(MHz)	(ms)	(kCC)	(kbps)
This work	Zynq-US	21	0	0	13 881	250	7.58	1 895	34
This work	Artix-7	24	0	0	13 385	90	21	1895	12
Mehrabi et al. [13]	Virtex-7	47	560	0	29 742	125	0.25	N/A	N/A
Asif et al. [14]	Virtex-7	19	1 0 3 6	828	N/A	87	0.73	63	351
Islam et al. [15]	Virtex-7	36	N/A	N/A	N/A	178	1.48	2630	173
Romel et al. [16]	Virtex-7	52	0	N/A	15 263	122	0.54	66	476
Arunachalam et al. [17]	Virtex-5	33	N/A	N/A	N/A	192	1.21	232	212
Roy et al. [18]	Virtex-5	40	0	N/A	N/A	43	0.60	26	1 667
Asif et al. [19]	Virtex-7	97	2799	7 452	N/A	73	2.96	216	1816

^a Throughput is estimated by authors as (Frequency ÷ CC) × 256.

The area metric comprises look-up tables (LUTs), digital signal processor (DSP) blocks, random access memory (RAM) blocks, and registers. Moreover, latency is measured in milliseconds (ms) and clock cycle (CC). Throughput is estimated as (Frequency \div CC) \times k, where k is the size of the output in bits [16].

Our implementation stands out for its minimal LUT count, surpassed only by [14]. However, [14] requires significantly more DSPs and RAM blocks, highlighting a critical efficiency trade-off. Unlike other designs such as [16] and [18]—which also avoid DSPs but demand higher LUTs—our approach efficiently manages operations with fewer resources. The lack of RAM and minimal register usage in our design further underscores its suitability for resource-constrained, low-power applications like crypto wallets, suggesting it could offer enhanced scalability and thermal performance compared to comparable architectures.

IV. CONCLUSION

The proposed hardware architecture for the SECP256K1 algorithm enhances resistance against SCA attacks by maintaining uniformity in register operations during the private key processing. Moreover, the architecture is designed for crypto wallet application, where it utilizes minimum resources and adheres to the industry standard for small, portable crypto wallets. Implementation results indicate that the proposed architecture requires, on average, 45% less LUTs compared to analogous implementations in literature. Future work will focus on performing detailed experiments on the device to demonstrate the security against SCA attacks and integrate the architecture into a crypto hardware wallet.

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