Modern Current Source Design

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Abstract

The underlying theme of this paper is to show three different approaches on how to make current sources more efficient, accurate, and mobile. First, using a body driven auxiliary amplifier to operate within a low input voltage range while also having the benefits of using a cascode current mirror. Next, a way to improve accuracy is through manipulating a Howland current source through digital signal processing, and poling to calibrate the output current source and account for any errors. Finally, an improved wide swing Wilson current mirror that is effective under low input voltage, and delivers high output resistance. All of these methods have common goal, and that is to introduce circuits more applicable to today's world.

Introduction

The demand for mobile technology has increased significantly within the last decade but, this comes at a price. These devices need to have a low-voltage power source while maintaining accuracy. In previous designs, the high-swing cascode current sources has been utilized to maintain high output resistance along with linearity and reduced noise. A proposed solution to keeping the high output resistance, linearity, and reduced noise while also having a low input voltage is the body-driven auxiliary amplifier.

There is a trend, especially in biomedical circuits that moving towards becoming smaller and more portable. Therefore, they have started using submicron CMOS technology. However, submicron technology requires operation on small input voltage so the device lasts as well as current mirrors that reduced the size. A proposed solution is to simply take a super wide swing wilson current source, which is a combination of a wide swing current mirror and a wilson current mirror. The wide swing current mirror will offer high output resistance and low voltage minimum, while the wilson current mirror will offer the current source to keep up a constant output current, when the load voltage changes. We will then use this wide swing wilson current source and modify it to deliver better results.

With the ever increasing technology of today's society, it is more and more important to achieve higher and higher accuracy on a smaller and smaller scale. One way of improving the accuracy of a current source is manipulating the Howland current source via digital signal processing and a sampling circuit to calibrate the output of this current source. Using the Howland current source model improves overall stability of the output, as it is not susceptible to temperature drift and aging of the current source.

Design Challenges

A. Low Voltage Input

Recent technology being developed is highly dependent upon low-voltage input for high voltage output devices most frequently for mobility purposes. High-swing cascade current-source configurations face major challenges for low-voltage CS-DACs. When the voltage input is lowered for a simple current source seen in figure 1, V_{DSQ} decreases, r_o decreases, and current mismatch increases [1].

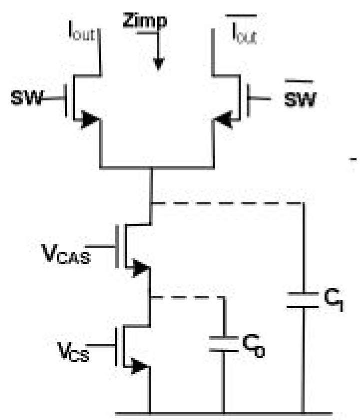

Figure 1 - Simple current source (HCCC) [1]

Current mismatch is when the output currents differs from the input current. These issues will decrease high-frequency linearity and increase signal noise. When current mirrors are implemented, a minimum current supply needs to be met, so biasing cannot be used to fix this problem. The configuration should be able to achieve large voltage swings.

B. Low Voltage Input for Biomedical Equipment

Biomedical circuits and integrated circuits in general demand large-voltage compliance current sources and current mirrors with high output impedance. Most biomedical instruments are starting to mirror "deep submicron" CMOS technologies so the power consumption is reduced and batteries can last longer. Although the smaller supply voltage has benefits, it also ensures low output resistance. Therefore we need a new way to apply current mirrors, sources, or sinks in a way that it can offer a very high output impedance over a large output voltage range [2].

C. Accuracy of Current Source

With electronics becoming smaller and smaller, it is important to have high accuracy on a small scale. Because the current being produced is sometimes on the micro scale, noise introduced by temperature drift and other interferences become more significant. This reduces the accuracy of current sources, so there is a need to reduce the susceptibility of the circuit to this noise and produce a stable output.

Proposed Solution

A. Body-Driven Auxiliary Amplifier

The proposed solution for improving the low voltage input current source is a body-driven auxiliary amplifier (Figure 2). This design resolved the design challenges better than a high-swing cascade current mirror. The body-driven current cell proved to have a significantly smaller $V_{DS(SAT)}$ than for a high-swing cascade current cell while still having a relatively large V_{OUT}[3].

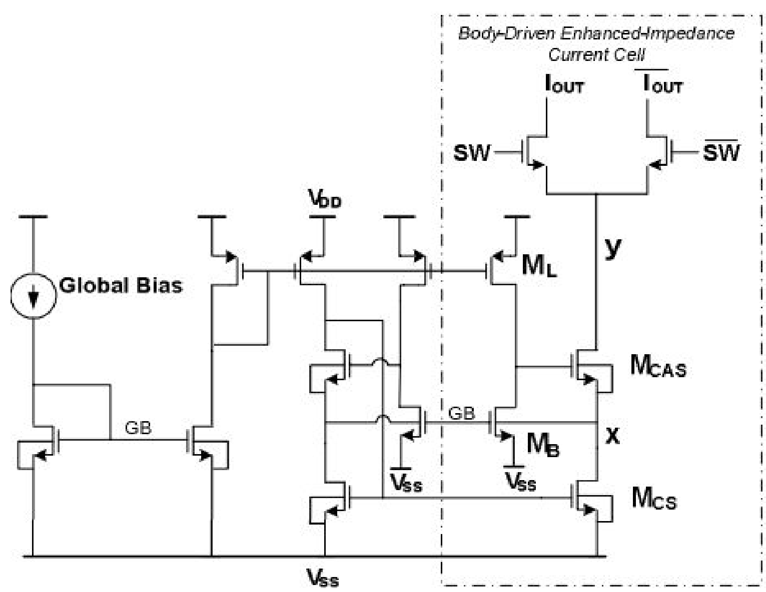

Figure 2 – Body-driven auxiliary amplifier [1]

The body-driven current cell resolves current mismatch by decreasing the minimum value of the ratio of width to length for the unit current source (W/L). This allows the capacitances to be lower. Lower capacitance decreases the necessary V_{DS} needed to keep the MOSFETs in saturation. Also, a smaller capacitance shifts the poles to higher frequencies, allowing for high-frequency linearity. The low output resistance that results from a smaller W/L ratio is resolved with a gain factor of the body-riven auxiliary amplifier configuration. Therefore, the output impedance is large while the voltage input is low, and due to the increased value of (W/L) the MOSFET has high-frequency linearity. Although the noise output is about the same for both configurations, both are still a fraction of the noise for a simple current source. The noise decreases since now the body is used as the input terminal.

This current source is considered an "enhanced-impedance" cell. The design allows for the impedance to increase without negatively affecting the frequency response [1]. The following equation represents the high circuit impedance:

$$R_{OUT} = A_{Vb} \times g_{m,sb} \times g_{m,cas} \times r_{o,sw} \times r_{o,cas} \times r_{o,cs}$$

$$\text{where: } A_{Vb} = \frac{g_{mb,b}}{g_{ds,b} + g_{ds,l}}$$

The g_m values are body transconductances. Table 1 shows the (W/L) comparisons discussed in this section [1].

Table 1: Comparison of BDCC and HCCC

Architecture	Unit Current Cell specifications						
	σ_I/I (%)	R_{req} (MΩ)	$(WL)_{CS}$ (μm^2)	$(W/L)_{CS}$	$V_{ov\text{-}CS}$ (mV)	I_{CS} (nA)	V_{out} (mV)
HCCC	0.5	6.4	<80	1	330	16 (+8)*	850
BDCC	0.5	6.4	80	5	150	16 +8	450

*if local bias used

B. High Swing Super Wilson Current Source

One current source that can increase the output resistance while at the same time operate with low voltage is a high swing super Wilson current source, as can be seen in figure 3. This circuit has I_{in} and I_{out} following through the M2 and M5 MOSFETs, respecti vely. The currents are compared and then M5 matches I_{out} to I_{in}, with the current sink as shown in figure 3.

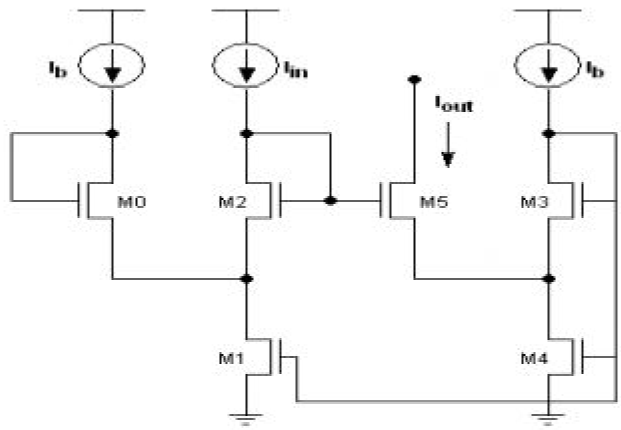

Figure 3: High Swing Super Wilson Current Source [2]

Generally, Wilson currents usually have an output resistance of the following:

$$R_{out} = gm*R_0^2 \qquad (1)$$

This can be seen in table 2, where a list of common output resistances are listed for many different types of current sources or mirrors. Therefore this Super Wilson Circuit has its own similar equation with some differences:

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$$R_{out} = gm*R_{05*}\, R_{01} \qquad (2)$$

Assuming same parameters and matched devices equation (1) and (2) will be equivalent.

Table 2: CMOS Current Mirrors Comparison

Configuration	Current gain	Output swing	r_{out}
Simple	$\frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}}$	V_{DSsat}	r_{ds}
Wilson	$\frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}}$	$V_{TH} + 2 \cdot V_{DSsat}$	$g_m \cdot r_{ds}^2$
Improved Wilson	1	$V_{TH} + 2 \cdot V_{DSsat}$	$g_m \cdot r_{ds}^2$
Cascode	1	$V_{TH} + 2 \cdot V_{DSsat}$	$g_m \cdot r_{ds}^2$
Triple Cascode	1	$2 \cdot V_{TH} + 3 \cdot V_{DSsat}$	$g_m^2 \cdot r_{ds}^3$
Triple Cascode	1	$2 \cdot V_{TH} + 3 \cdot V_{DSsat}$	$g_m^2 \cdot r_{ds}^3$
High-compliance I	$\frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}}$	$2 \cdot V_{DSsat}$	$g_m \cdot r_{ds}^2$
High-compliance II	1	$2 \cdot V_{DSsat}$	$g_m \cdot r_{ds}^2$
Regulated-cascode	$\frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}}$	$V_{TH} + 2 \cdot V_{DSsat}$	$g_m^2 \cdot r_{ds}^3$

To improve upon this Super Wilson Circuit displayed in figure 3, I_b or the bias currents can be replaced by a current source with PMOS devices and gates connected to the voltage source. Also M0 will be replaced by I_{in} and M1 will disconnect from the gate of M5 and connect to the gate of M1. This can be observed in figure 4.

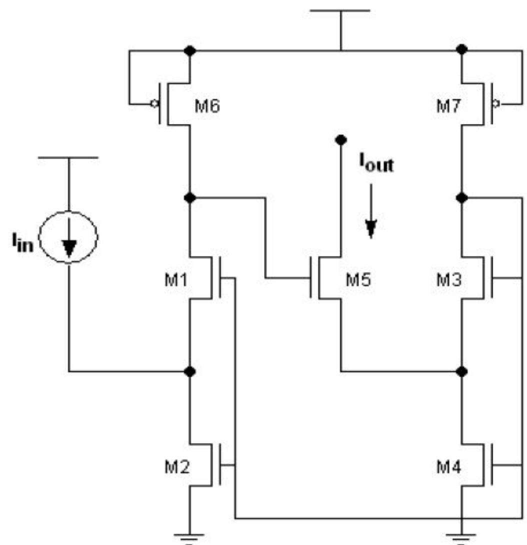

Figure 4: Improved Current Source [2]

As you can see in figure 4, the changes to the Super Wilson Circuit creates a symmetric current source that will compare I_{in} and I_{out}, without using the auxiliary current sources seen before. Then the M5 transistor will make I_{out} fit in the compliance range so the input and output currents are matched. M2-M4 are part of the current mirror they are used to achieve high output impedance. The modified M1 is part of the cascade now, and M6-M7 also act as an active load and increase the output impedance. Therefore, the total output resistance can be approximated as:

$$R_{out} = (g_{m6} || g_{m1})^* g_{m2} {}^* R_{05} {}^* R_{01} {}^* R_{01} \qquad (3)$$

The factor of the R_{out} is increase by is about $(g_m || g_m)^* R_0$

C. Improved Howland Circuit

The system of this current source can be divided into three parts: the control circuit, the current generator, and the sampling circuit. In the control circuit, commands for the parameters of the current source are received by a microcontroller which then is passed through a 16 bit D/A converter. The output current is determined by an improved model of the Howland current source shown in figure 6.

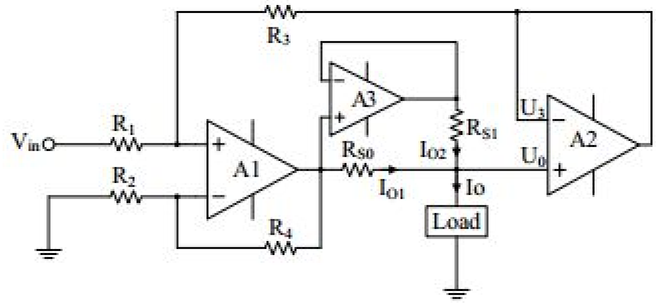

Figure 6: Improved Howland current source [4]

The output of the D/A converter is connected to Vin of figure 6, and the output current is Io connected across the load. The output of figure 6 can be modeled by the equation:

$$V_{OUT} = V_{REF}L + \frac{(V_{REF}H - V_{REF}L) \times N}{65536}$$

Where V_{ref}Hand V_{ref}L are the high and low reference voltages of D/A converter. The op-amp labeled A3 is connected in series with R_{s1}, which is equivalent to R_{s0}. Using this configuration ensures I_{o1} and I_{o2} each provide half of the total output current, which effectively increases the amount and stability of output current. The output current can be derived to be:

$$I_0 = \frac{U_2 - U_0}{R_s} \times 3 = \frac{3R_1}{R_3} \times \frac{U_I}{R_s}$$

Using this equation, it is apparent that by manipulating the ratio of R_3 and R_1 can allow the user to effectively set the value of the output current.

Noise is a major problem in analog circuits, so digital circuitry is used to calibrate the output of figure 6. The principle behind the digital circuitry is to provide a high resolution output with minimal error. The output of figure 6 is connected to a feedback loop consisting of a sampling resistor, a filter and a programmable instrumentation amplifier, and an A/D converter. Measurements are taken across the sampling resistor, and any common signals between the two ends of the resistor are not amplified by the instrumentation amplifier.

The output of the instrumentation amplifier is connected to a low pass filter (figure 7) to suppress low noise interference. The value of R_a and R_b, and C_a and C_b should be the same to prevent a common mode error. C_2 is added in this circuit to prevent this error from occurring.

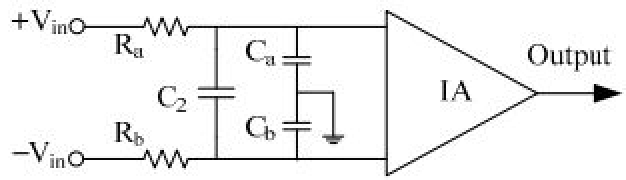

Figure 7: Low pass filter [4]

An AD converter converts the analog signal to a digital signal to be read by the microcontroller. The performance of the AD converter operates based on the state machine in figure 8.

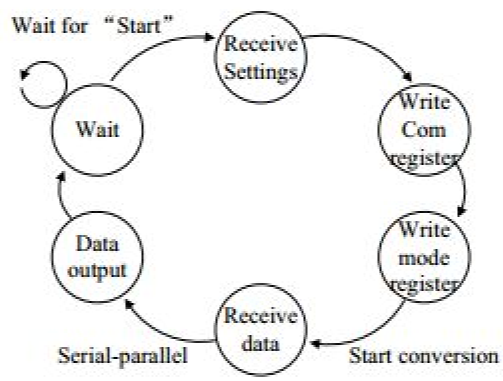

Figure 8: AD converter state machine [4]

The AD converter receives the conversion mode, then the communication register is written. This determines which register is going to be operated, and whether data is going to be read or written. The write mode makes sure the AD conversion is under the specified mode, then the data is output to the microcontroller. The code written to the microcontroller compares the signal it receives to the desired accuracy of the output current and makes according compensations. The whole system operates based on the block diagram in figures 9 and 10.

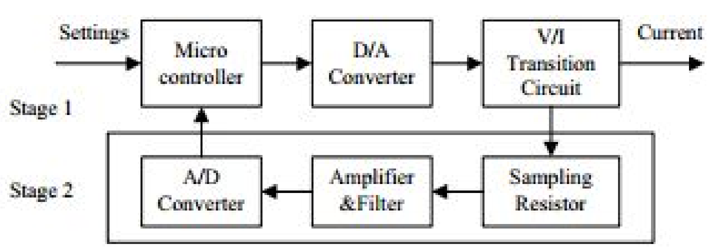

Figure 9: System block diagram [4]

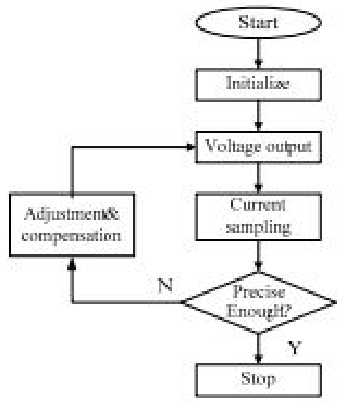

Figure 10: System block diagram [4]

Results

A. Body-Driven Auxiliary Amplifier

The graphs in figures 11 and 12 exemplify the BDCC's superior output resistance in comparison to the HCCC. This was tested for both a single current cell and an entire digital-to-analog converter. The output current of the BDCC increases more rapidly than the HCCC

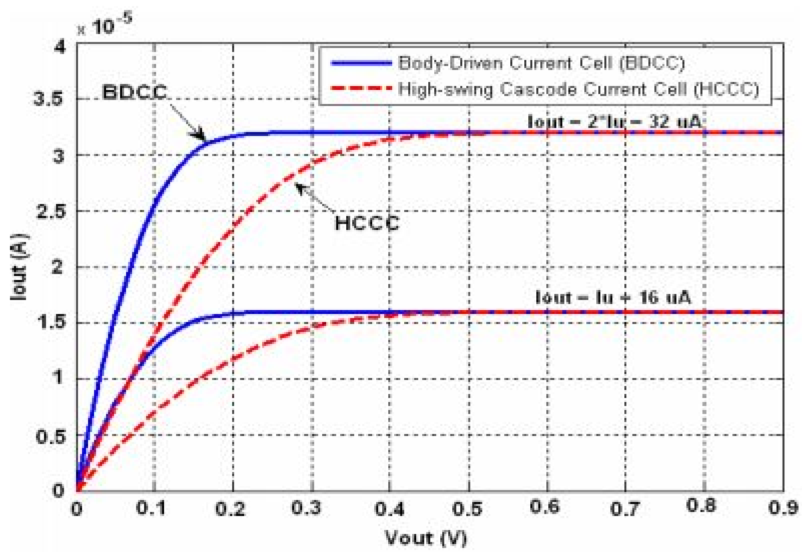

Figure 11: Comparative I_{OUT} for BDCC and HCCC

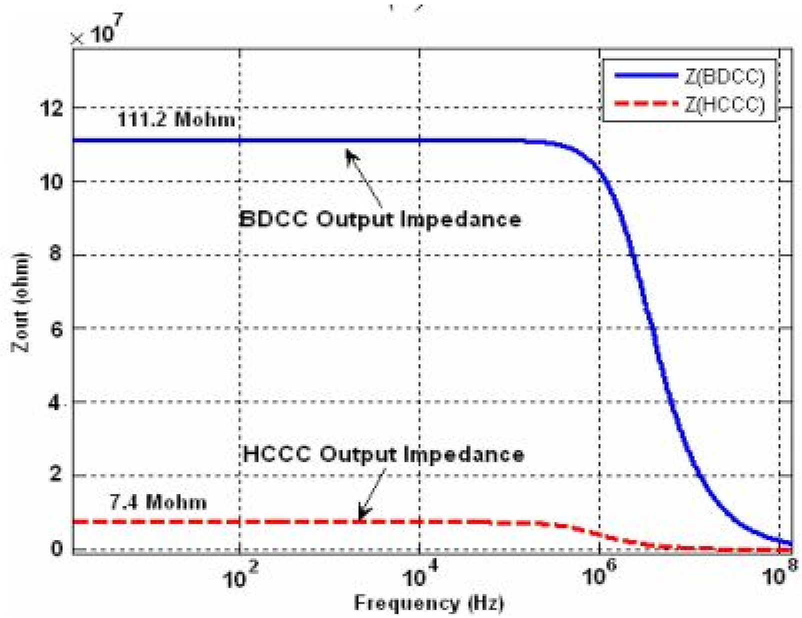

Figure 12: Comparative Impedance for BDCC and HCCC

B. High Swing Super Wilson Current Source

The performance of circuit within its compliance region is or DC response fits perfectly flat at 1 V which was the target for these new sub-micron devices, as seen in figure 5 [2]. Table 3 shows how much closer the improved current mirror is to the Super Wilson current mirror, not only in closeness to I_{in} but also in a having a larger impedance [2].

Figure 5: DC Response of the Improved Circuit[2]

Performance Comparison

	Vdd=1.8V		
	I_{in} = 40µA	I_{in} = 5µA	
	I_{out} (A)	I_{out} (A)	Impedance Ω
Proposed current mirror	3.92E-05	4.85E-06	5.50E+04
Super Wilson current mirror	4.12E-05	6.40E-06	4.36E+04

Table 3: Performance Comparison[2]

C. Howland current source

This configuration drastically improves the overall accuracy of the current source, but at the cost of excess components. The error in the output of the current source (when producing a desired output current of 50 mA) was 5 µA. Table 4 shows the output current based on the desired setting, with and without load.

Setting	Test results (without feedback)	Test results (with feedback)	Overall accuracy ±(% of full scale)	1-day stability ±(% of full scale)	Temperature coefficient ±(ppm of setting)
100µA	102.8µA	101.2µA	0.012	0.015	40
1mA	1.004mA	1.001mA	0.010	0.020	35
10mA	10.005mA	10.001mA	0.010	0.030	30
50mA	50.009 mA	50.004 mA	0.040	0.050	25
-100µA	-96.7µA	-98.7µA	0.013	0.017	40
-1mA	-996.5µA	-998.5µA	0.015	0.020	35
-10mA	-9.994mA	-9.997mA	0.030	0.020	30
-50mA	-49.992mA	-49.995mA	0.050	0.060	30

Table 4: Output current results

<u>Conclusion</u>

The overall goal of this project has been completed. The body driven amplifier improves the low input voltage operation at a .1V, while it increased output resistance to about 111.2 mega ohms. The improved super swing wilson current mirror, has improved the low voltage operation to 1V at 40 micro amps, which is ideal for biomedical technology, the accuracy of the input to output current mirror is improved by a 3% error, and the output resistance has increased by 100 kilo ohms. The feedback on the Howland current source has significantly reduced the error on input to output currents. Overall, by using different types of current sources, and techniques we have been able to discover new ways to improve current sources as well as the application of the overall circuit.

References

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