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SELF-HEATING AND THERMAL NOISE MINIMIZATION OF THE SERIAL-LINK TRANSMITTER

The simulations of the serial-link transmitter are implemented considering the aging process of the MOSFET device within 10 years. Two techniques are proposed to minimize the aging impact on the transmitter output eye diagram. For this purpose, control logic is added. After one data bar is transmitted, the control logic exchanges the states between the operating and disabled output stages, hence decreasing self-heating and thermal noise.

Keywords: self-heating, thermal noise, serial-link transmitter, shift register, electro-migration.

Introduction. Nowadays, technological processes actively continue to shrink the transistor's channel and Moor's law is still driving the silicon market. This tendency increases the device concentration in the same area of die. On the other hand, while the transistor channel gets actively shrunk, supply voltages do not follow dynamics and do not get decreased by the same per-cent. These two scenarios, leading to power dissipation increase in the die area, hence supporting the self-heating phenomenon of on-chip CMOS devices and interconnections. The self-heating phenomenon itself causes multiple undesirable effects inside the die, which should be considered during the IC design process to be sure of the identity of simulation and post production results. The temperature increase due to self-heating increases the currents of silicon devices, and at the same time reduces conductivity and the applicable current concentration of interconnections in both ways, complicating the satisfaction of electro-migration rules. Besides, higher temperature implies more thermal noise in all on-chip devices and interconnections which will create more jitter on the transferred data. The two points mentioned above are not the only bottlenecks caused by self-heating, the CMOS device aging process suffers from self-heating as well. The amount of interconnections and the CMOS transistors self-heating can be calculated by equations (1) and (2) respectively [1,2]:

$$\Delta T = I^2 * R * R_{th}^{i}, \quad (1)$$

$$\Delta T = I_{ds} * V_{ds} * Z_{th}, \quad (2)$$

where ΔT is the amount of the increased temperature, I - the current flowing through resistor, R - the electrical resistance of interconnection and R_{th}^{i} - the thermal resistance of the interconnection, I_{ds} is the transistor's current, V_{ds} - the drain-source voltage and Z_{th} - the thermal impedance. In the static regime, Z_{th} can be written as R_{th} which can be expressed by electrical resistance equation. In the general case Z_{th} is expressed by equation (3) [2]:

$$Z_{th} = \frac{R_{th}}{1+j*\omega*C_{th}*R_{th}}. \quad (3)$$

The impact of self-heating on the thermal noise can be expressed by equations (4) and (5) respectively for resistors and semiconductor devices [2]:

$$V^2 = 4k\Delta TR, \quad (4)$$

$$I^2 = 4k\Delta T\gamma g, \quad (5)$$

where $k = 1.38 * 10^{-23}$ is the Boltzmann constant, V^2 and I^2 are the noise power per unit bandwidth, ΔT – the temperature increase, R - the interconnection resistance, γ - the technology dependent constant which is about 2.5, g is the transistor's drain-source, i.e., the same as R_{on}^{-1} [3]. V^2 is expressed as V^2/Hz and I^2 as A^2/Hz. Equation (5) can be expressed with V^2 by (6):

$$V^2 = I^2 * r_0^2, \quad (6)$$

where r_0 is the transistor's channel resistance in the saturation mode [4].

The Self-heating impact on the serial-link transmitter. Self-heating can have a serious impact for circuits, where large currents flow. Such circuits are the transmitter and receiver systems (Fig.1) where during the data transfer, large currents flow from the transmitter to the receiver through the channel. Current will be drawn from the output stage of the transmitter, so transistors and interconnections of the output stage will suffer from self-heating which will increase the thermal noise being a source of random jitter for the transmitted data. Under these conditions, the receiver circuit should be complicated to correctly equalize the noisy input signal. This scenario could be prevented by self-heating characteristics investigation of the transmitter's output stage and provision of corresponding solutions for thermal noise reduction.

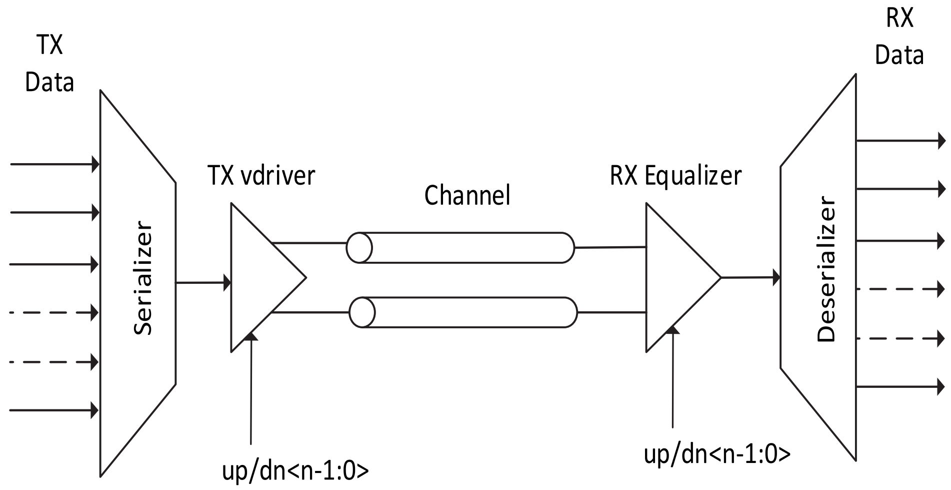

Fig.1. Transmitter receiver system

The transmitter's output stage consists of multiple parallel units which have the same sizes and resistances. The parallel units could be enabled or disabled by resistance calibration circuit to provide a correct resistance value for proper resistance termination with the channel and receiver input stage. Otherwise signal reflections will appear. The parallel units are controlled with a thermal code. The number of enabled units depends on the calibration code which varies from the process, temperature and chip to chip variations. Once calibration is completed, the calibration code is written into registers to be used by the transmitter's output stage.

The parallel units get at the inputs of the data bar, which should be transmitted to the receiver. In the data transition process through the channel, only the enabled units of the transmitter's output stage are involved. The total current to charge and discharge the receiver input capacitance is drawn by the data transition transistors of the active units, so these transistors are the ones which will suffer from self-heating. To properly estimate the self-heating during the data transfer, the transmitter's output stage was simulated, self-heating and thermal noise were measured. Self-heating results are presented in Table 1.

The results presented in Table 1 include not only the transistor's self-heating, but also the heating caused by the thermal coupling between the transistors and wires, which could be calculated by equations (7):

$$\Delta Tcouple = A * \Delta TFET, \tag{7}$$

where $\Delta Tcouple$ is the heating amount caused by thermal coupling of transistors and interconnects, A - the thermal coupling coefficient, $\Delta TFET$ - the transistor's self-heating. The thermal coupling coefficient depends on the distance between the wire and the transistor. With the distance increase, it gets smaller, the maximum value it can have is 1.

Table 1

Self-heating of the transmitter's output stage

MLayer	x/y_coord	ΔTFET [K]	A	Δtcoupl [K]
m0	(9.016,12.288)	26.85	0.69	18.53
m0	(9.016,12.016)	26.85	0.67	17.99
m1	(8.904,12.288)	26.85	0.57	15.30
m1	(8.904,12.016)	26.85	0.56	15.04
m2	(9.128,12.288)	26.85	0.51	13.69
m2	(9.128,12.016)	26.85	0.5	13.43

During simulation, 32 active units of the transmitter's output stage were used. The heating of each unit is almost the same, as all units are of the same size, and properly matched. In Table 1, the results for a single unit and for its interconnections with different metal layers are presented. The coordinates point out the part of an interconnection where the measurement is carried out.

The thermal noise for the transistors and interconnections are measured and presented in Table 2.

Table 2

Thermal noise of the transmitter's output stage

MLayer	x/y_coord	ΔTFET [K]	ΔTcoupl [K]	FETnoise $[A^2/Hz]$	Mnoise $[V^2/Hz]$
m0	(9.016,12.288)	26.85	18.53	7.11E-23	3.07E-21
m0	(9.016,12.016)	26.85	17.99	7.11E-23	2.98E-21
m1	(8.904,12.288)	26.85	15.30	7.11E-23	2.53E-21
m1	(8.904,12.016)	26.85	15.04	7.11E-23	2.49E-21
m2	(9.128,12.288)	26.85	13.69	7.11E-23	2.27E-21
m2	(9.128,12.016)	26.85	13.43	7.11E-23	2.22E-21

Thermal noise of the proposed circuit with double output units

The proposed technique with a controlled number of units. Self-heating and thermal noise reduction could be reached if current consumption from the units of the transmitter's output stage were reduced. Current drawn from the transmitter can not be changed, as it depends on the channel parameters, transmitter's output and receivers input resistance and capacitance.

It is proposed to replace the registers, where resistance calibration code is written, with the shift register (Fig.2).

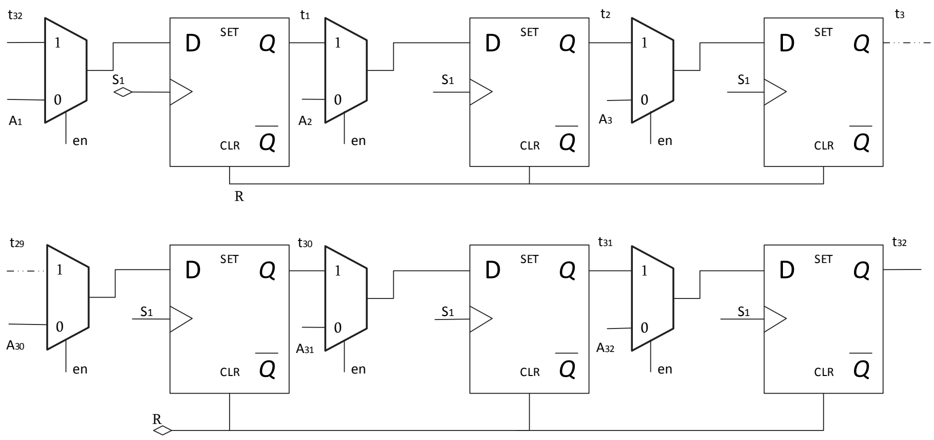

Fig.2. Shift register structure

The shift register will periodically shift the calibration code so that the part of the enabled units should be disabled and vice versa. This allows each unit to cool down. The switching from active to passive units is controlled by a counter, which gives an overflow signal. The switching happens after a whole bar of data bits are already transmitted. This approach prevents kickback noise occurrence of the leg switching process on the transmitted data, so additional jitter will not occur. The full data bar of usb3.1 is 132bits (Fig.3) [5].

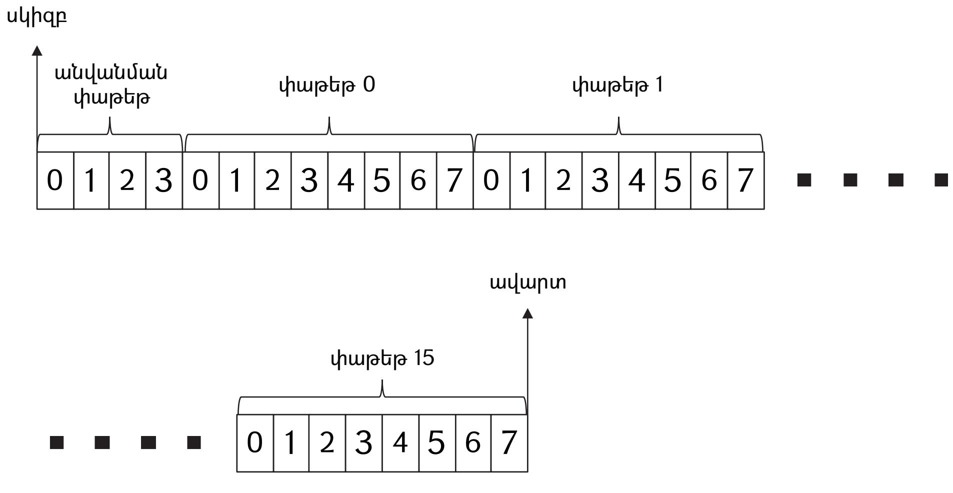

Fig.3. USB3.1 data bar order

The transmitters' output stage is simulated, self-heating and thermal noise results are presented in Tables 3 and 4.

Table 3

Self-heating of the transmitter's output stage with the proposed technique

MLayer	x/y_coord	ΔTFET [K]	A	Δtcoupl [K]
m0	(9.016,12.288)	19.72	0.69	13.61
m0	(9.016,12.016)	19.72	0.67	13.21
m1	(8.904,12.288)	19.72	0.57	11.24
m1	(8.904,12.016)	19.72	0.56	11.04
m2	(9.128,12.288)	19.72	0.51	10.06
m2	(9.128,12.016)	19.72	0.5	9.86

Table 4

Thermal noise of the transmitter's output stage with the proposed technique

MLayer	x/y_coord	ΔTFET [K]	ΔTcoupl [K]	FETnoise $[A^2/Hz]$	Mnoise $[V^2/Hz]$
m0	(9.016,12.288)	19.72	13.61	5.23E-23	2.25E-21
m0	(9.016,12.016)	19.72	13.21	5.23E-23	2.19E-21
m1	(8.904,12.288)	19.72	11.24	5.23E-23	1.86E-21
m1	(8.904,12.016)	19.72	11.04	5.23E-23	1.83E-21
m2	(9.128,12.288)	19.72	10.06	5.23E-23	1.67E-21
m2	(9.128,12.016)	19.72	9.86	5.23E-23	1.63E-21

The summarred results are presented in Table 5.

Table 5

Summary results

	Initial version	Proposed technique
Device self-heating [K]	26.85	19.72
Metal self-heating [K]	18.53	13.61
Device thermal noise $[A^2/Hz]$	7.11E-23	5.23E-23
Metal thermal noise $[V^2/Hz]$	3.07E-21	2.25E-21

Conclusion. The technique is presented to reduce self-heating and thermal noise in a serial-link transmitter. The proposed technique shifts the calibration code and in that way disables the heated units. This allows each unit to cool down. The control logic is added to control the shifting process. With the proposed technique self-heating is decreased by 7K.

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ԻՆՔՆԱՏԱՔԱՑՄԱՆ ԵՎ ՋԵՐՄԱՅԻՆ ԱՂՄՈՒԿՆԵՐԻ ՆՎԱԶԵՑՈՒՄԸ ՀԱՋՈՐԴԱԿԱՆ ՀԱՂՈՐԴՉՈՒՄ

Կատարվել է հաջորդական հաղորդչի ինքնատաքացման և ջերմային աղմուկների գնահատում: Առաջարկվել է միջոց՝ ինքնատաքացման և ջերմային աղմուկների նվազեցման համար: Հաջորդական հաղորդչում ներառվել է կառավարման հանգույց, որը յուրաքանչյուր ինֆորմացիոն փաթեթի ուղարկման ավարտից հետո փոխարինում է հաջորդական հաղորդչի ելքային հանգույցի ակտիվ միավորները պասսիվներով: Առաջարկված մոտեցումը թույլ է տալիս, որ հաջորդական հաղորդչի ելքային հանգույցի միավորները գտնվեն հանգստի ռեժիմում, այդ կերպ նվազեցնելով ինքնատաքացումը և ջերմային աղմուկները:

Առանցքային բառեր. ինքնատաքացում, ջերմային աղմուկ, հաջորդական հոսքուղու հաղորդիչ, բարեյան շեղիչ, էլեկտրամիգրացիա:

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МИНИМИЗАЦИЯ САМОНАГРЕВА И ТЕПЛОВОГО ШУМА ПЕРЕДАТЧИКА ПОСЛЕДОВАТЕЛЬНОГО КАНАЛА

Реализованы симуляции передатчика последовательного канала с учетом самонагрева и теплового шума. Предложена техника минимизации самонагрева и теплового шума выходного каскада. Добавлена управляющая логика, которая после передачи одного информационного пакета меняет состояния между рабочими и отключенными единицами выходного каскада. Эта техника позволяет единицам выходного каскада быть в отключенном режиме во время работы, снижая самонагрев и тепловой шум.

Ключевые слова: самонагрев, тепловой шум, передатчик последовательного канала, устройство быстрого сдвига, электромиграция.