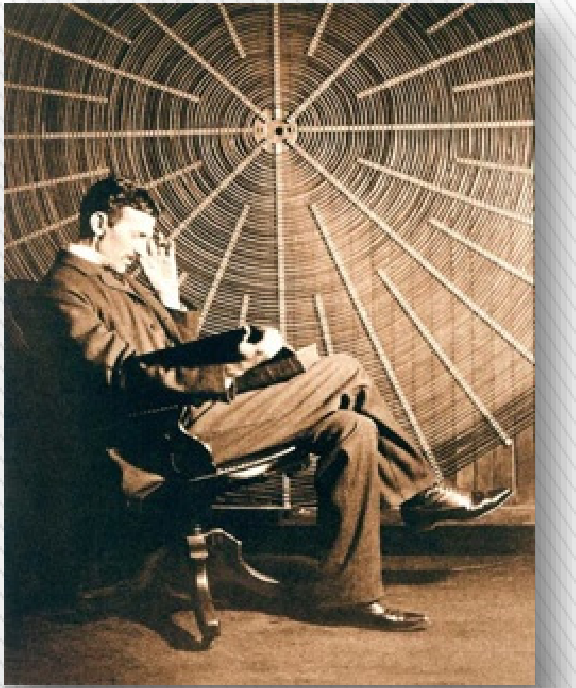

IC1301 -WiPE

Optical Power Delivery and Temperature Data Transmission Using a Single Light Emitting Diode

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WIPE
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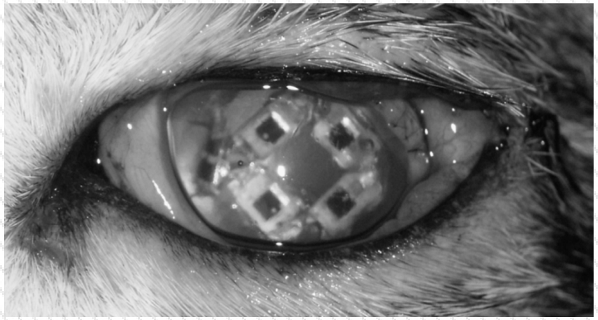
Main Objective

- Solve the low photodiode voltage and conversion efficiency problems associated with optically powered smart microsystems
- To demonstrate a compact energy management framework for harvesting optical energy from a LED as well as transmitting data using the same LED.

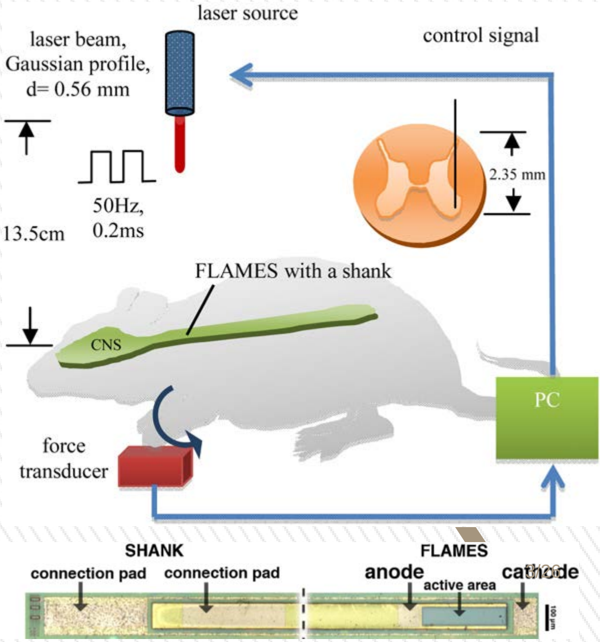
Optical energy harvesting microsystems

- Optical (photovoltaic) energy harvesting delivers greatest power in smallest volume
- Favorable for wireless, batteryless smart microsystems that are required to be very small (~1 mm^3)

Commercialized IC for specimen tagging purposes [1]



Epi-retinal electrical stimulator powered by an array of PIN diodes [2]



Individually adressable microstimulators [3]

…but there is a catch

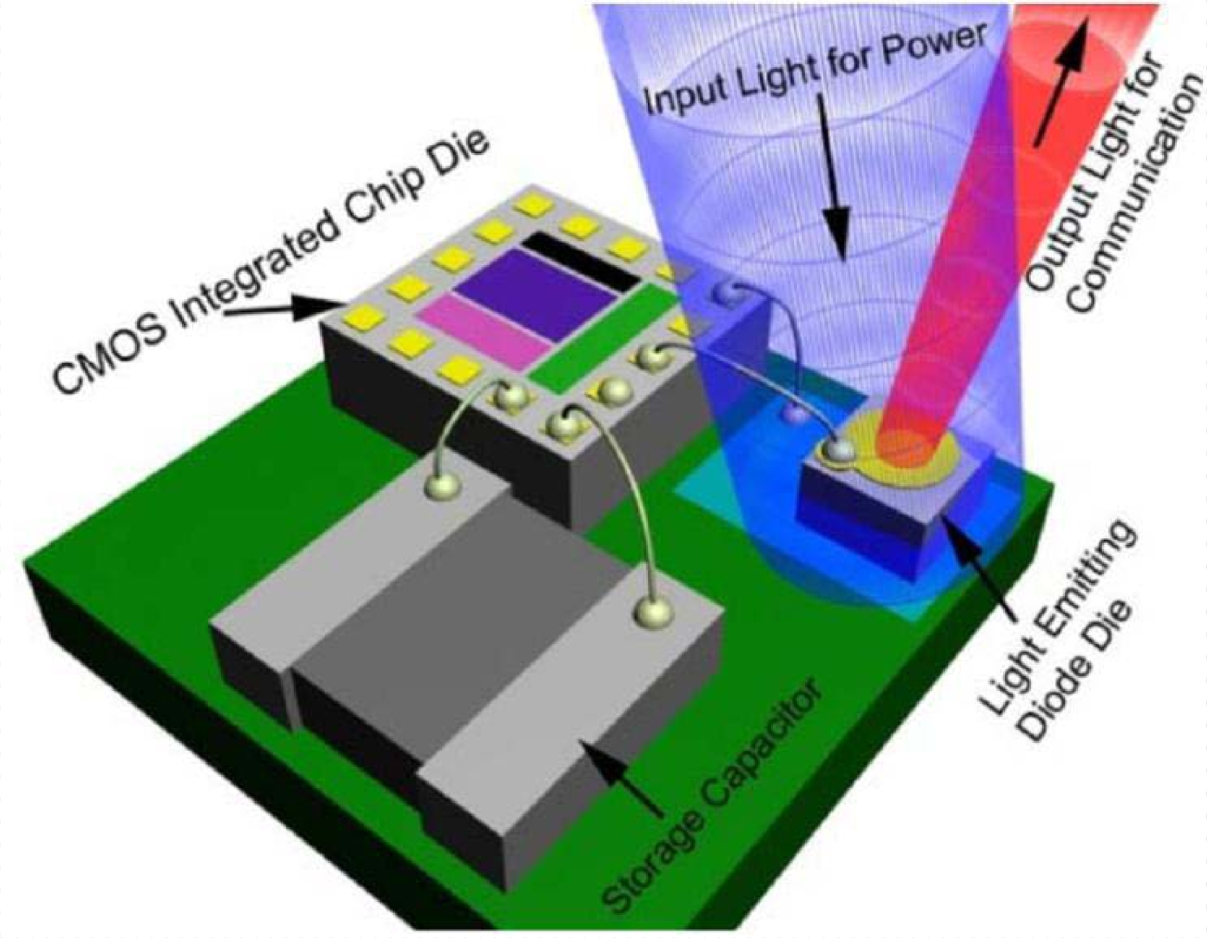
- A silicon photodiode can only supply around 0.6V under illumination. Very problematic if sensors and analog electronics are to be integrated into the design
- Connecting on-chip CMOS photodiodes in series is problematic and inefficient [4]. SOI photodiodes can be connected in series without efficiency loss [5]. However, SOI wafers are *VERY expensive*.
- A charge pump can be used to elevate 0.6V to around 1.2V at greatly reduced efficiency [6].
- On-chip photodiodes take up *expensive* silicon real estate. The additional charge pump must be large as well, to support large current loads. This leaves very small area functional blocks such as sensors, processor units, memory, etc.

Transmission of data

- A smart microsystem is expected to communicate with its user, transmitting sensor readings, device ID, etc.
- Standard silicon photodiodes have NO ability to emit photons. For optical transmission, a LED or laser diode must be used.
- Additional antenna for RF transmission increase the overall size.

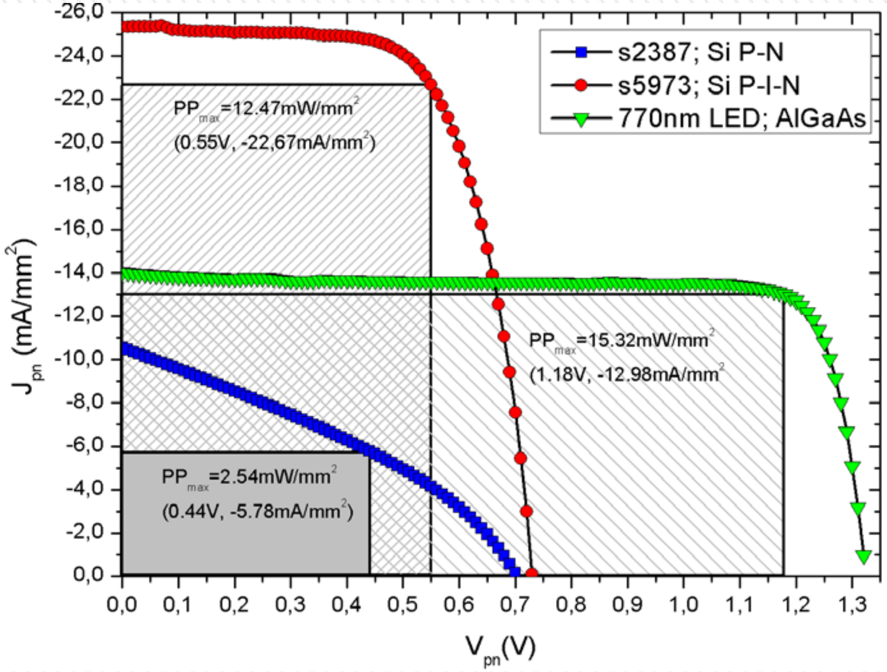
Typical current microsystem solutions:
Optical power transfer, RF data transmission

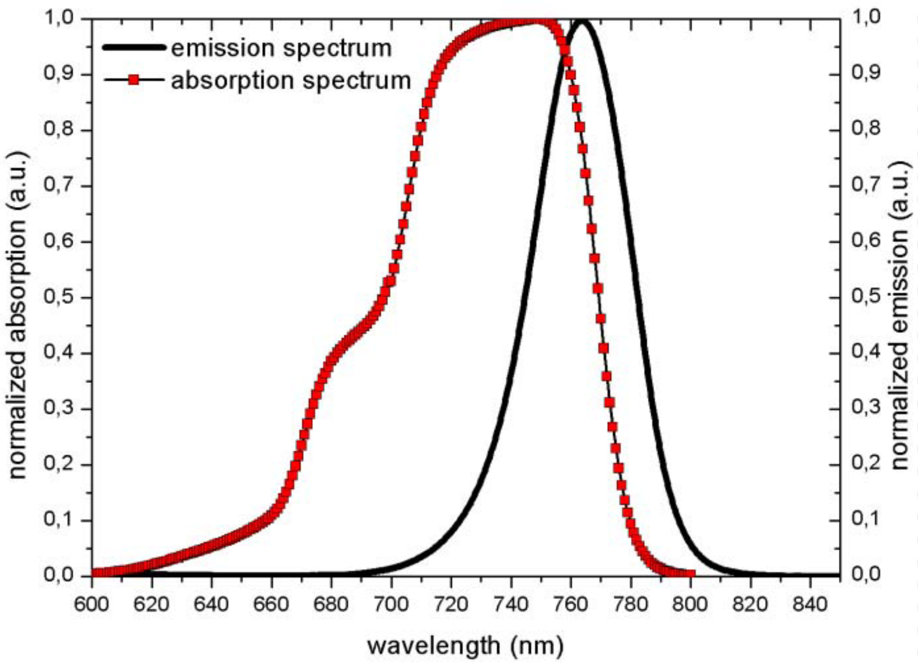
Our solution to the problem



- » **Use a single LED to harvest energy and transmit data**
  - **Maximizes the utility of the unavoidable external component**
  - **Greater power conversion efficiency**
  - **Usable open circuit voltage without need for elevation.**
  - **Saves on-chip area**

LED as a photovoltaic cell





» A 770nm LED is used to collect energy from 680nm laser beam delivering **1.2 V** and >1mA. Silicon PIN photodiode can deliver **0.6 V**.

» **LED has 22% optical to electrical energy conversion efficency for this wavelength.**

"A great solar cell has to be a great LED."

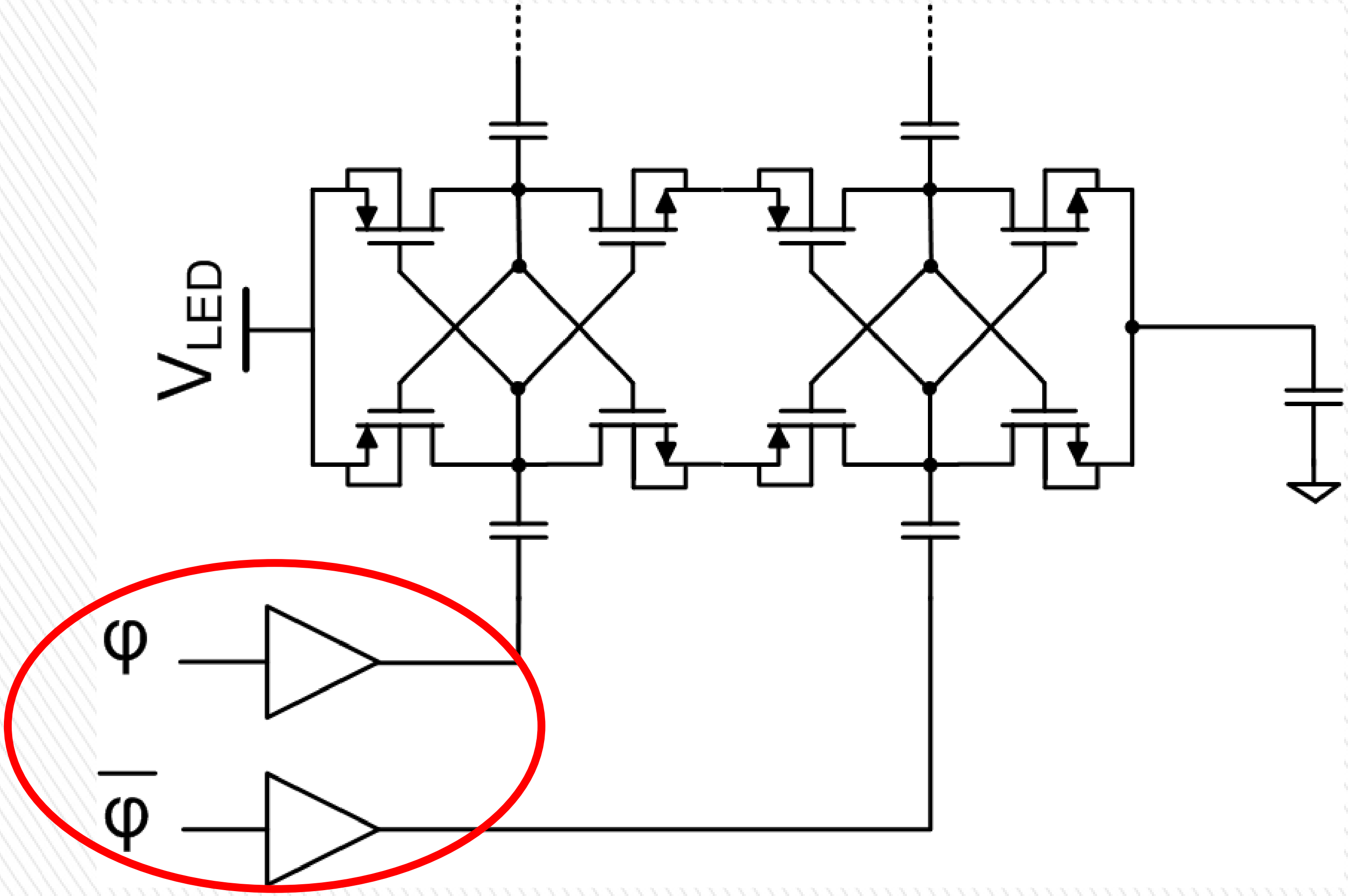
Eli Yablonovitch, "Solar Cell Breaks Efficiency Record", *IEEE Spectrum*, 2011.

Problem: Transmitting with the LED at LOW supply voltage

- The open circuit voltage of the LED must be increased to forward bias it and emit photons.
- Classically, a charge pump charges a large capacitor relatively slowly. The charge-up of the large capacitor is slowed down by the output current of the charge pump, as the charge pump has a less than unity power conversion efficiency.

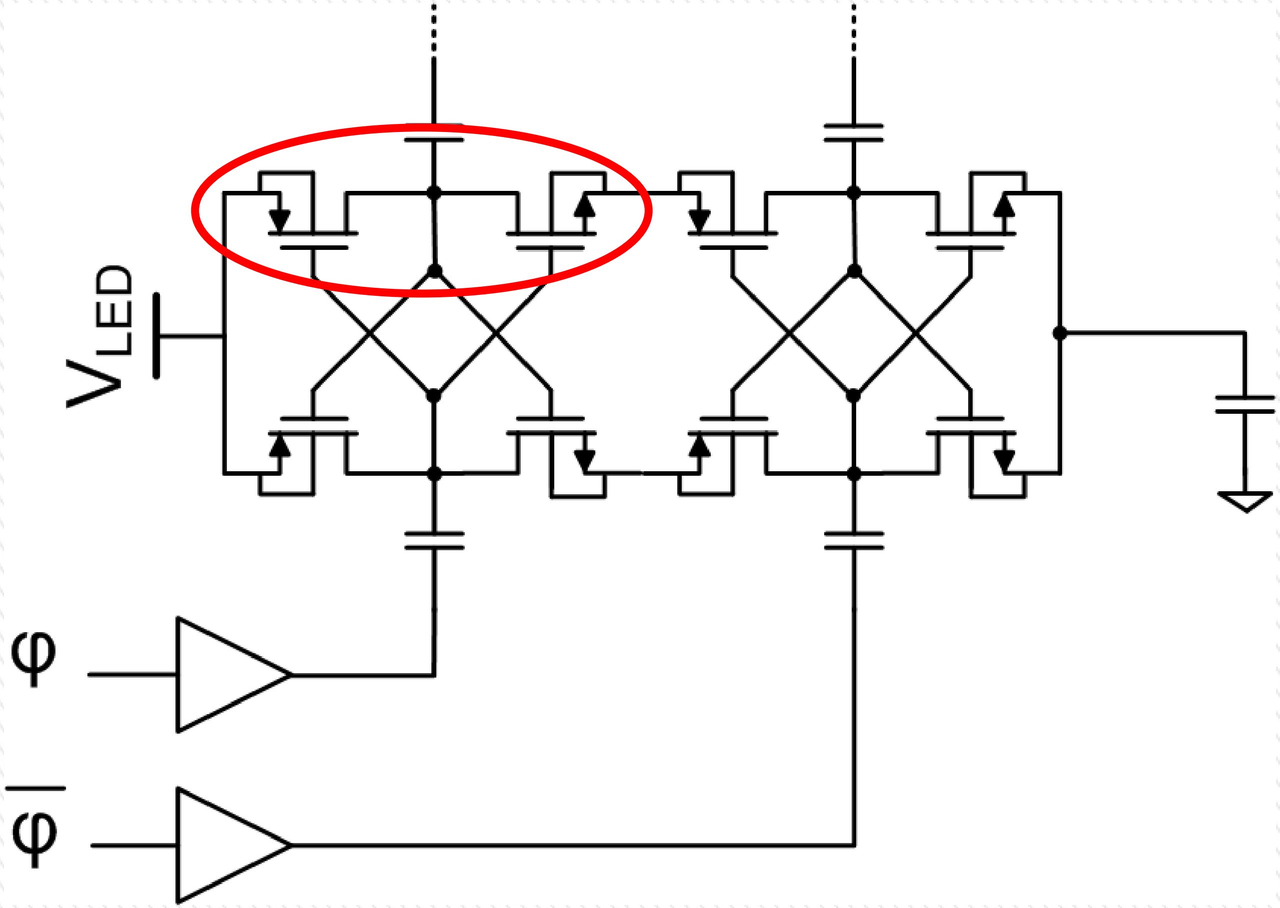
Charge Pump Inefficiencies - 1

- Clock buffers drain power (load capacitance ~ 1pF, f~100kHz-1MHz, ΔV ~ 1V)



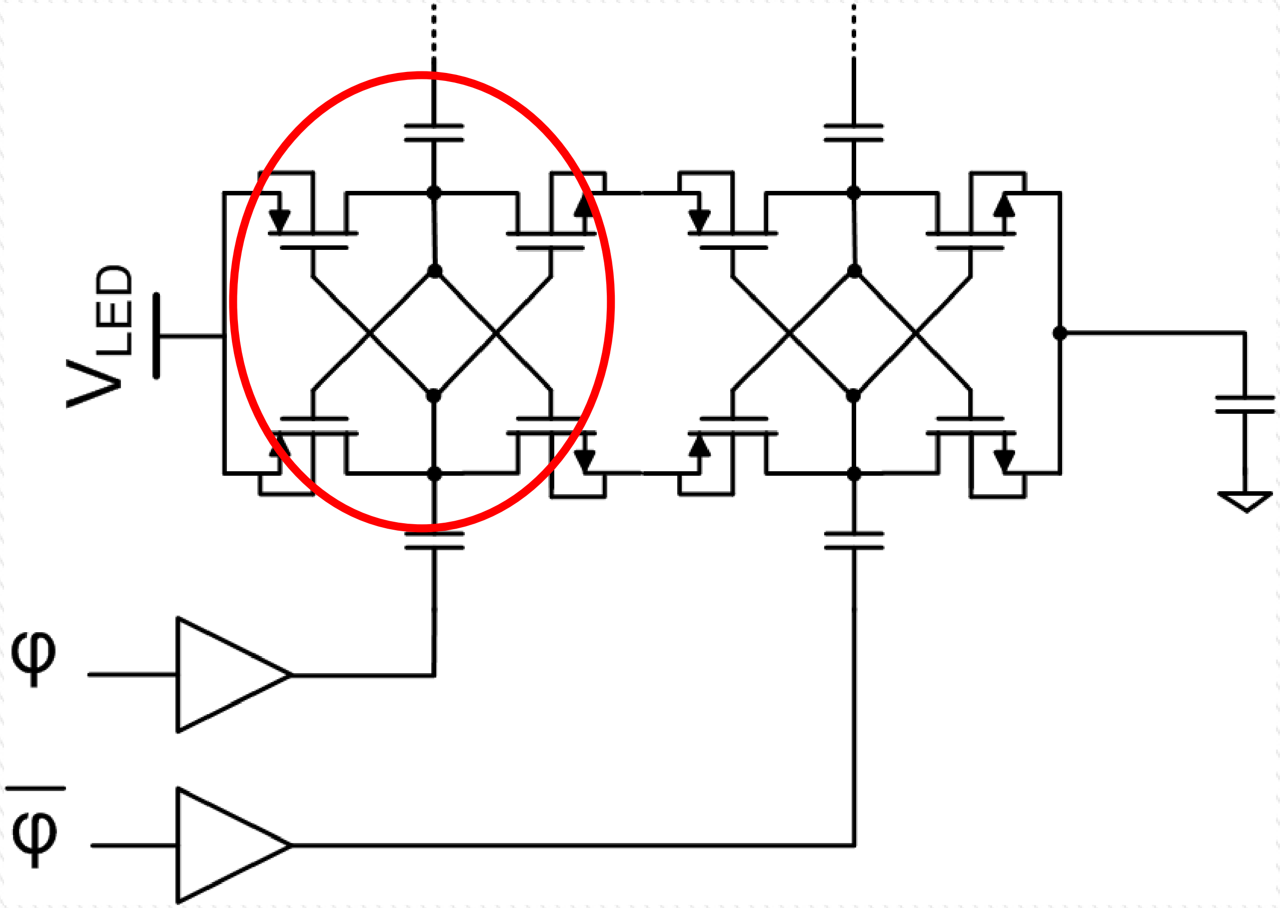
Charge Pump Inefficiencies - 2

- Threshold voltage drops reduce voltage gain from the ideal 2xVDD per stage (the featured architecture limits this by employing positive feedback). Channel resistance is also a hinderance.



Charge Pump Inefficiencies - 3

» Charge sharing between pump capacitor and parasitic capacitances (switch transistors tend to be WIDE)



Observations

- Actively pumping charge into a large capacitor with high frequencies takes much power, and takes a long time if the current ouput is low. Therefore it is wasteful of precious energy.
- The elevated charge is needed for a short instant in our application, whereas charge pumps are optimized to deliver sustained power, or high voltage with NO current load.

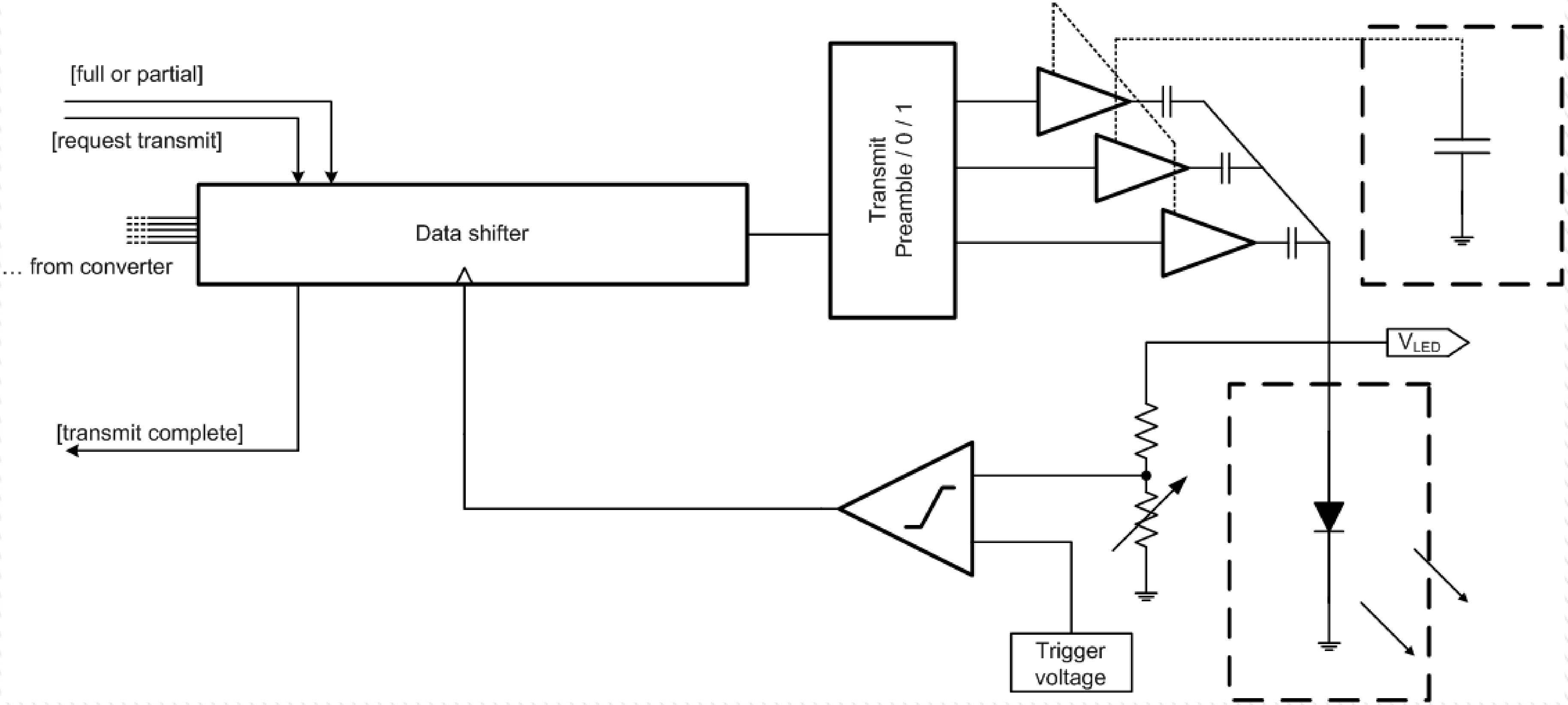
A new approach

- Let the LED current charge the capacitors by itself, then connect two capacitors in parallel.
- This boosts the total voltage instantaneously, overcoming the energy barrier for photon emission. Requires NO additional power consumption.

Implementation

- Pulser units are designed to be modular. They are connected in parallel to send consecutive pulses. Only one external capacitor is necessary; each row has its own dedicated internal capacitor

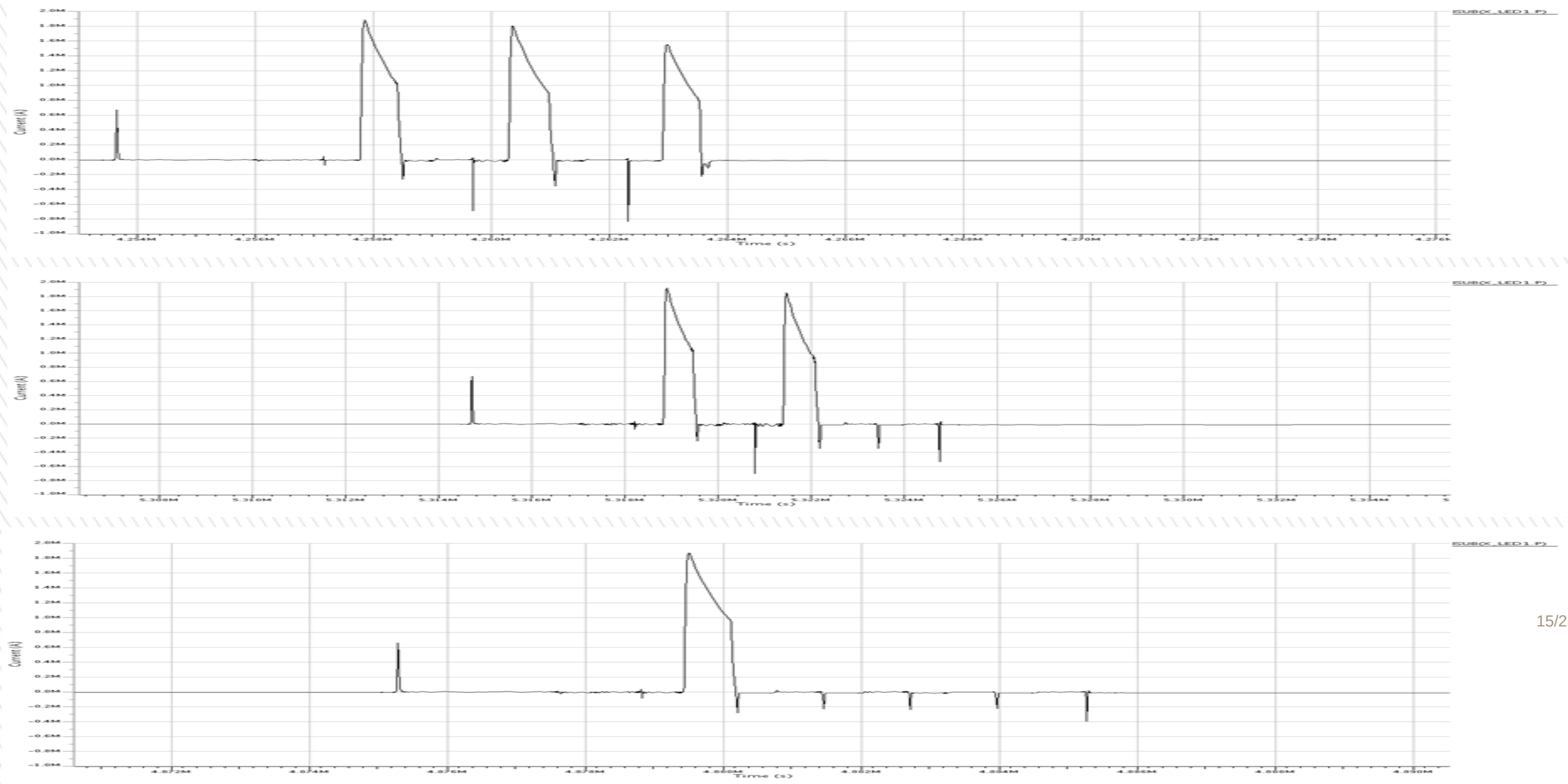
Transmitter Architecture



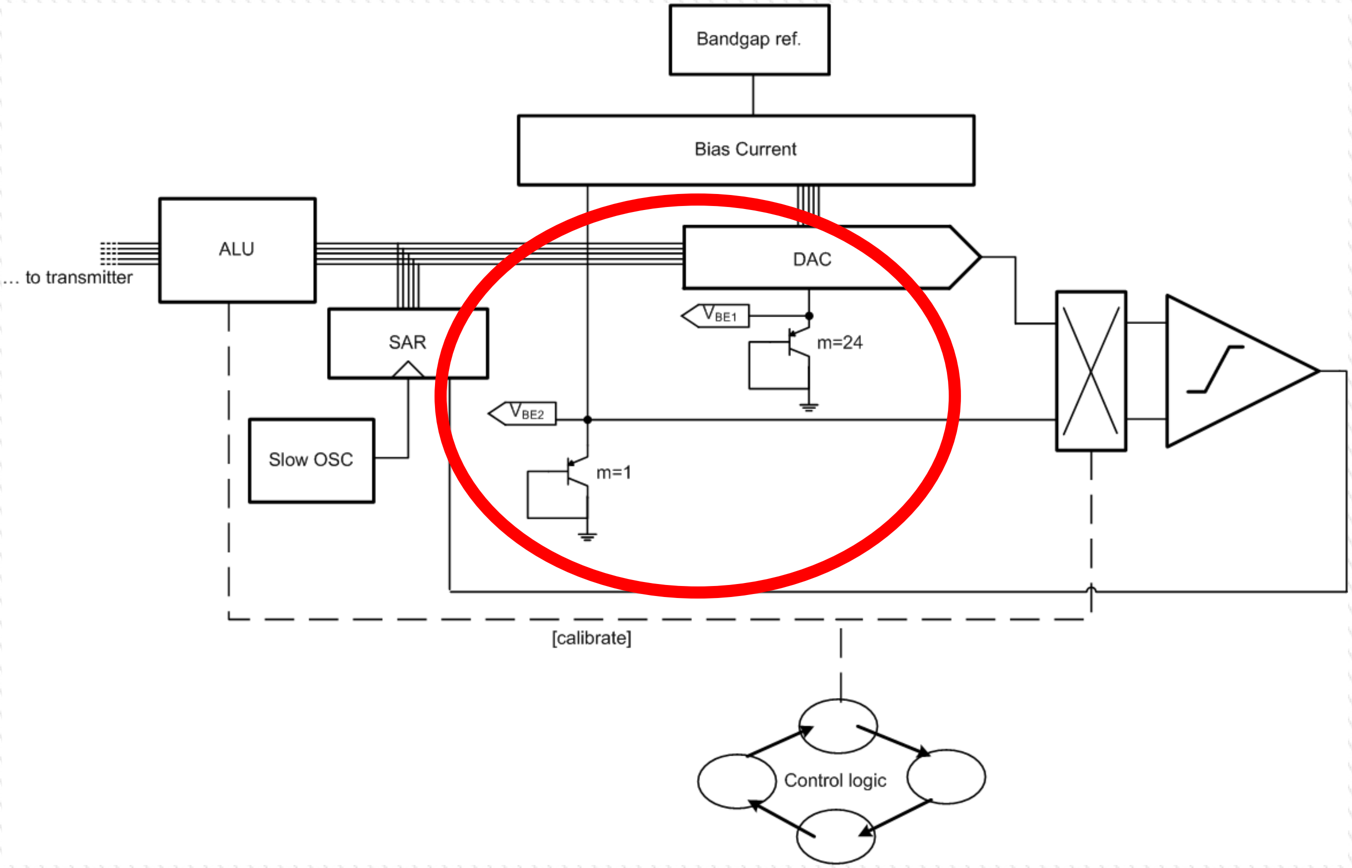
- Multiple pulsers can be triggered to send a stream of pulses. A single pulse signifies logic 1, double pulses signify logic 0, and triple pulses signify the preamble symbol. After all the pulses signifying the transmitted bit are sent, capacitors are alowed to be charged up.

Pulser operation

» Parallel pulser units are triggered consecutively to create photon emission

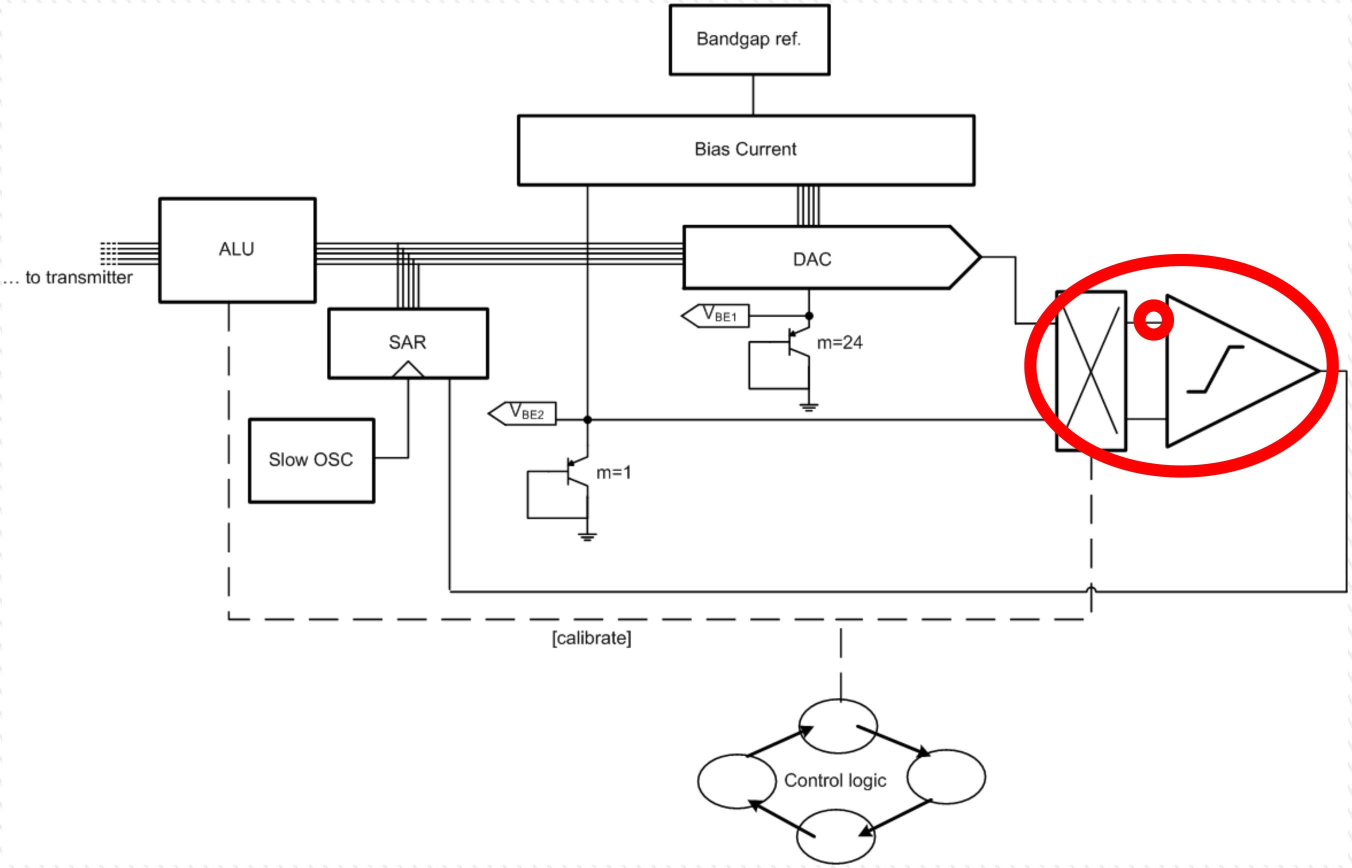


Temperature Measurement -1



- $\Delta V_{BE} = V_{BE2} - V_{BE1} = kT/q \times \ln(M)$; M=24 in our design.
- A resistive DAC generates a voltage such that $V_{DAC} + V_{BE1} = V_{BE2}$; thus directly generating ΔV_{BE}
- Voltage steps in the order of 20µV is necessary to achieve 0.1°C resolution
- Comparator offset is random and in the order of 1mV ! Offset cancellation is necessary

Temperature Measurement -2



- First measurement: $V_{BE2}=V_{DAC}+V_{BE1}+V_{OFFSET}$
- Switch inputs!
- Second measurement: $V_{BE2} + V_{OFFSET} = V_{DAC}+V_{BE1}$
- V_{OFFSET} is calculated and stored for future measurements. After this calibration step, the offset voltage is subtracted from future measurements without further need for calibration.
- Calibration is repeated periodically to cancel out effects of drift, noise, etc.

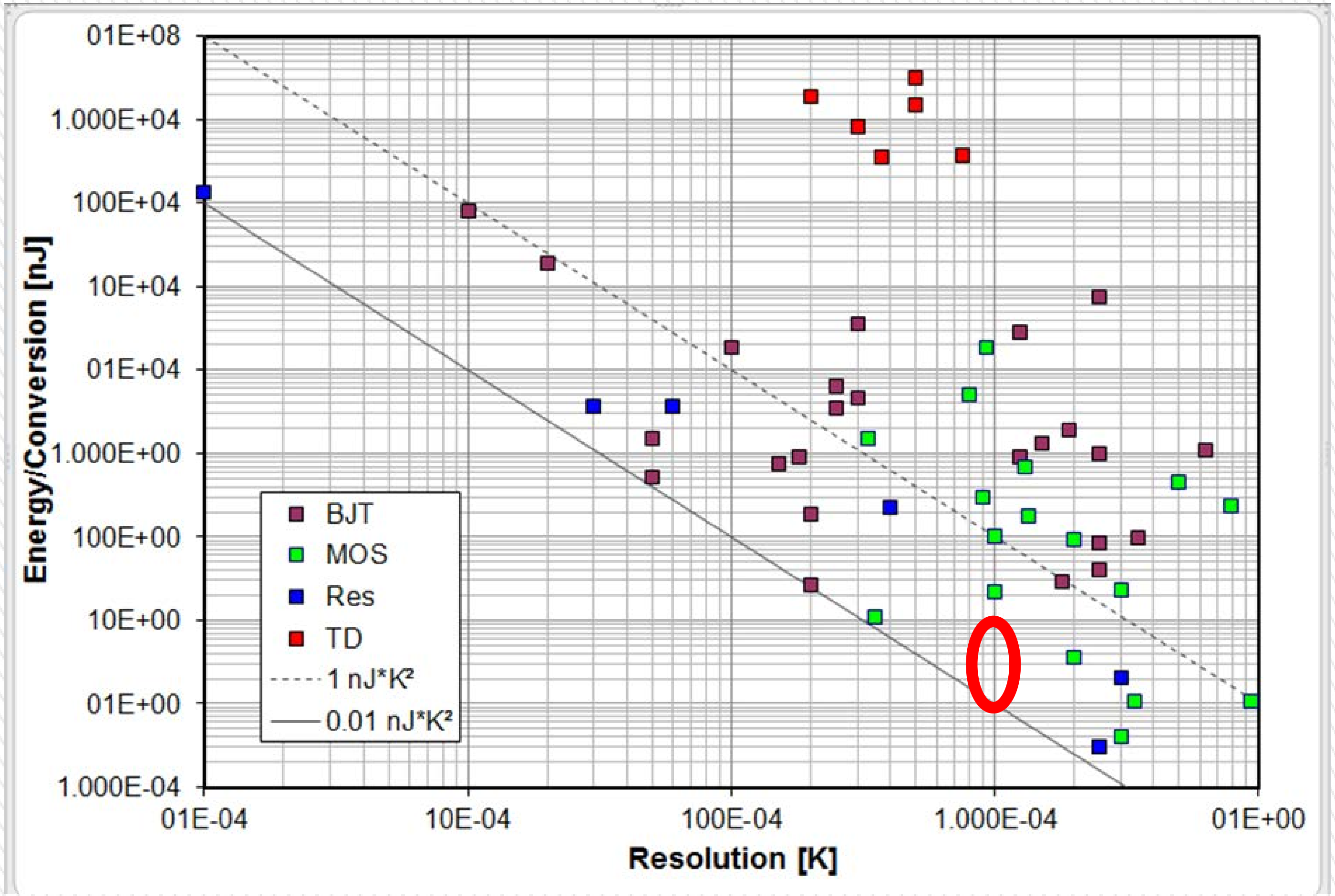
Temperature measurement -3

- After a full calibration measurement, N consecutive measurements are made without switching inputs; the offset is subtracted digitally form those measurements.
- Moreover, the tempreature change is expected to be relatively slow, so full measurements (14bits) unnecessary as only a few LSBs will change from measurement to measurement.
- So after the calibration measurement, only 7LSB of the temperature code is updated. This saves time and most importantly, energy! Increases the data rate WHILE saving energy.
- If the short measurements drift too much from the initial calibrated measurement, the smart sensor initiates another calibration cycle, and keeps updating this temperature code with new data!

Overall Power and Energy Consumption

- 5-6µA @ 1.2V; 6-7.2 µW power
- 4nJ/ conversion for full calibration measurement, 1nJ for consecutive partial updates. For 1 full and 9 partial measurements, the average energy consumption is 1.3nJ
- Transmitter side; < 1nJ per pulse

Figure of Merit



- » Source: Makinwa, K., Smart Temperature Sensors Survey (http://ei.ewi.tudelft.nl/docs/TSensor_survey.xls

Future work

- 5-10µW is available to the LED in direct sunlight.
- How about indoors operation? (10-100nW @0.8-1V)
- ΔV_{BE} temperature sensing needs 1µA or more bias current. Subthreshold CMOS temperature measurements can achieve 10nA current consumption but highly INACCURATE
- Leakage currents will become VERY important to deal with
- LED transmitter circuit must be revised

Acknowledgements

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