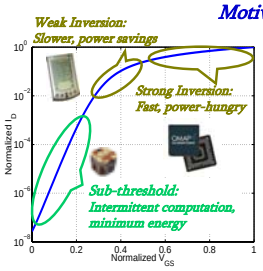
Voltage Scalable Switched Capacitor DC-DC Converters for Ultra-Low-Power On-Chip Applications

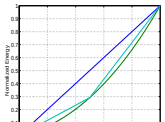
Yogesh K. Ramadass, Anantha Chandrakasan
Massachusetts Institute of Technology, Cambridge

Ultra-Low-Voltage Operation?

Motivation



Ultra-Dynamic Voltage Scaling

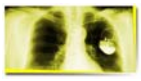


Applications

Environmental Sensors

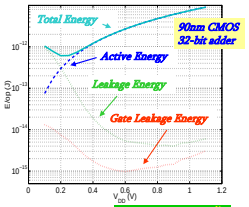
NASA/JPL

Medical Devices



Ambient Intelligence

Minimum Energy Operation



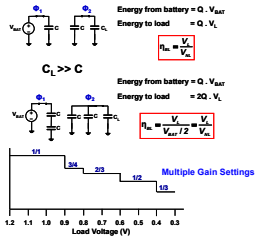
$$E_{Total} = C_{eff} V_{DD}^2 + W_{eff} L_{DF} K C_g V_{DD}^2 e^{\frac{-V_{DD}}{nV_T}}$$

- Operate at lowest voltage to just meet performance constraints
- If performance is not a constraint, operate at the minimum energy point

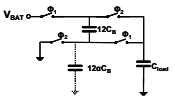
Switched Capacitor DC-DC Converters

Efficiency Loss Mechanisms

Conduction Loss



Bottom-Plate Parasitic Loss



$$E_B = 24 C_B V_{BAT} \Delta V$$

$$E_{BP} = 12\alpha C_B \frac{V_{BAT}^2}{4}$$

$$K_p \frac{V_{BAT}}{\Delta V} = \frac{E_{BP}}{E_B} = 0.125\alpha \frac{V_{BAT}}{\Delta V}$$

Switching and Control Loss

$$E_{SW} = nC_{ox} W L V_{BAT}^2$$

$$E_{SW} = n\beta C f_s V_{BAT}^2 \quad W \sim C, f_s$$

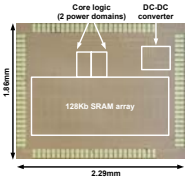
$$K_s f_s \frac{V_{BAT}}{\Delta V} = \frac{E_{SW}}{E_B} = n\beta f_s \frac{V_{BAT}}{\Delta V}$$

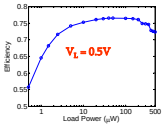
Topology Dependent — Technology Dependent

$$\eta_{ov} = \frac{E_L}{E_B + E_{BP} + E_{SW} + E_{CONT}} = \left(1 - \frac{\Delta V}{V_{NL}}\right)\left(\frac{1}{1 + K_p \frac{V_{BAT}}{\Delta V} + K_s f_s \frac{V_{BAT}}{\Delta V} + K_c \frac{V_{BAT}}{C\Delta V} + \frac{I_{leak}}{C\Delta V f_s}}\right)$$

- Pre-factor is due to linear efficiency loss
- Contribution of other losses decrease as ΔV goes up
- There is an optimum ΔV for any given topology
- Larger C improves efficiency

Sub-V_T MSP430 Microcontroller



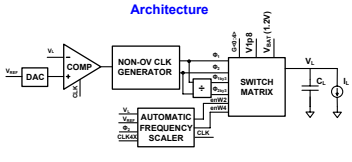


Process	65nm CMOS
Area	
DC-DC Converter	0.12mm²
SRAM	1.36mm²
Logic	0.14mm²
Performance	
Minimum Energy Point	V_{DD} = 500mV
Minimum Functional V_{DD}	V_{DD} = 300mV

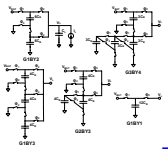
- 65nm SoC functional down to 300mV
- Embedded DC-DC converter
- Extremely small area
- Scalable output voltage

0.18µm 1mA SCDCDC Converter

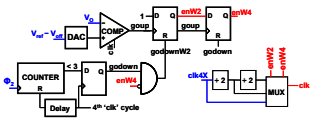
Architecture



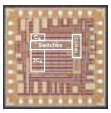
Gain Settings



Automatic Frequency Scaler

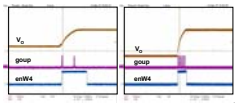


Die Photo

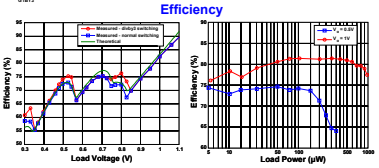


0.57 mm²

Transient Response



Efficiency



- Overload comparator is used to increase switching frequency at higher loads
- At low load, switching frequency is halved using a counter mechanism
- enW2 and enW4 determine switching frequency out of divided versions of clk4X

Conclusions

- On-chip Switched Capacitor DC-DC converters can provide up to 10 - 20mA load current
- Multiple Voltage Domains possible
- Achieves above 80% efficiency
- Technology Scaling helps to reduce area and switching losses

Sponsorship and Chip Fabrication: Texas Instruments, National Semiconductor and DARPA