E-Textile Battery-Less Walking Step Counting System with <23 pW Power, Dual-Function Harvesting from Breathing, and No High-Voltage CMOS Process

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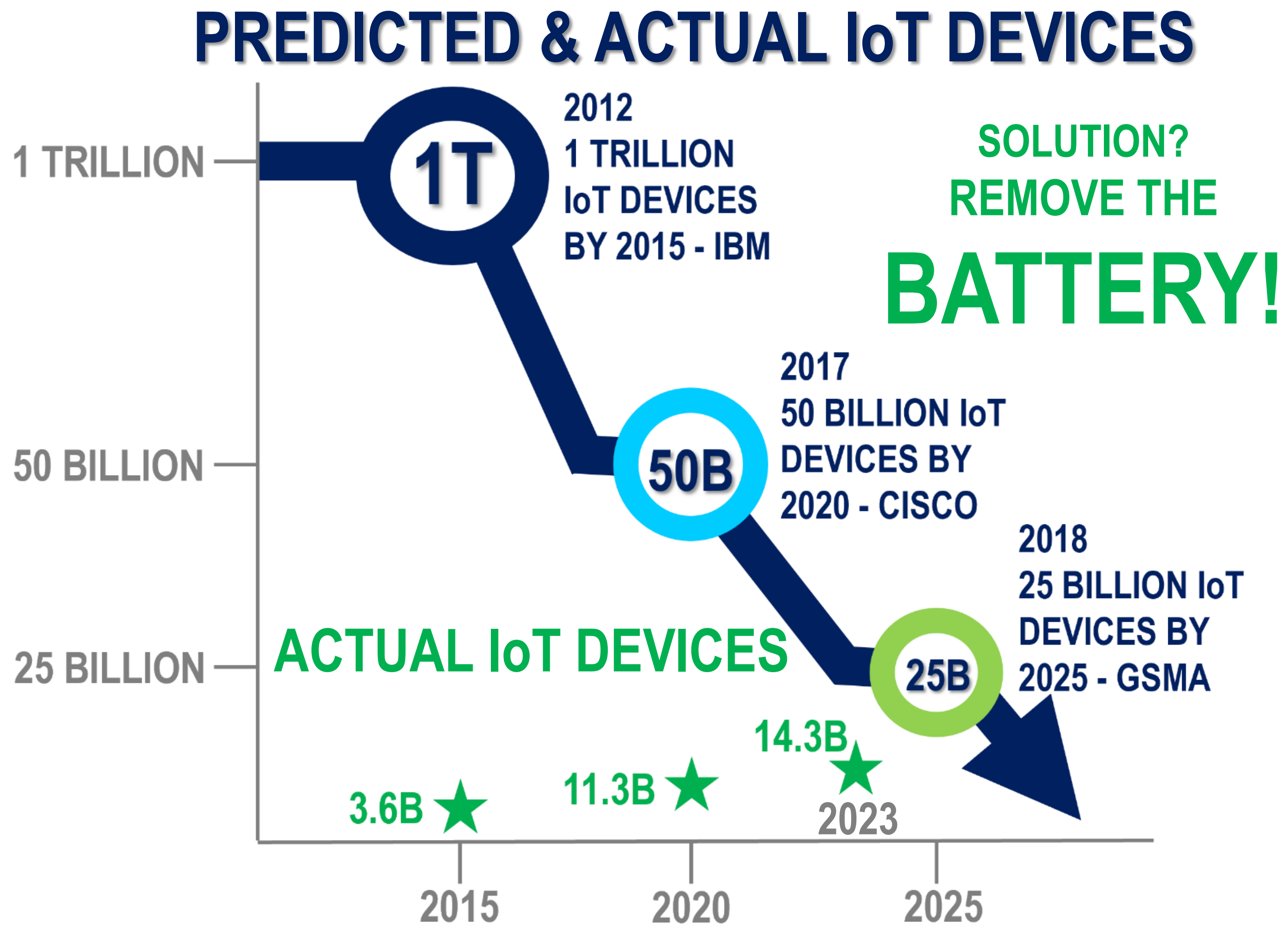
Integrated Circuits and Embedded Systems

Outline

- Background and Motivation
- Details of our Work
- System Measurements
- Comparison of Results with Previously Reported Work
- Conclusion
- Miscellaneous

Background and Motivation

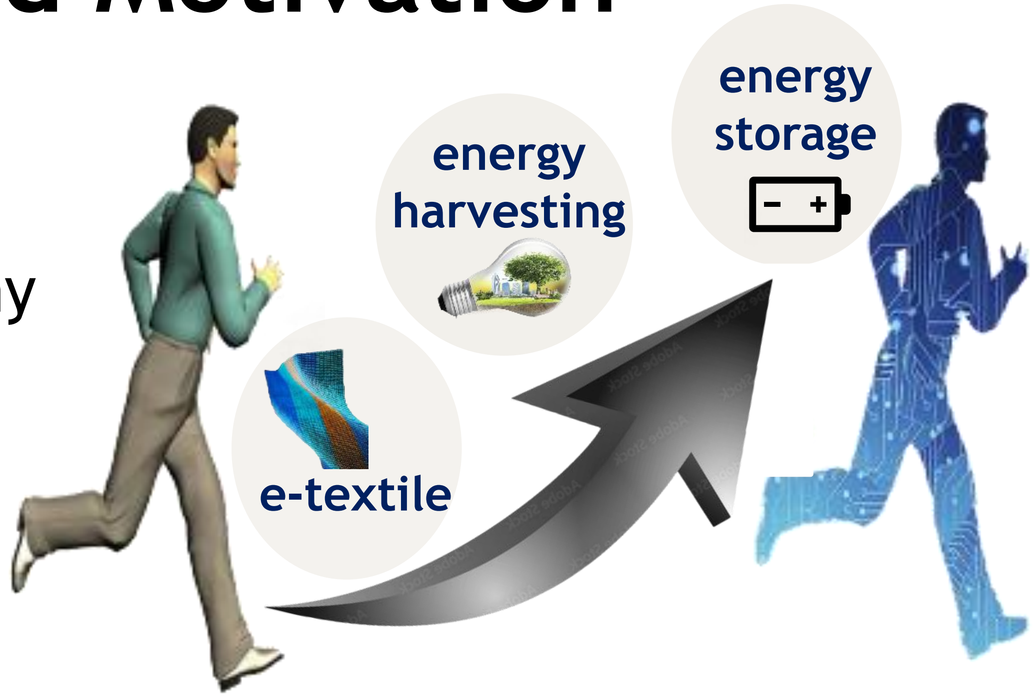


- The predicted IoT sensor nodes keeps decreasing,
- Problem : Battery!
  - 1 trillion sensor world demands:
  - ~3 year life span of battery
  - 913,242,009 BATTERY REPLACEMENTS everyday
- Solutions : ***Self-powered systems***
- ***Conformable Storages***
  - *form-fitting devices with unprecedented design freedom*

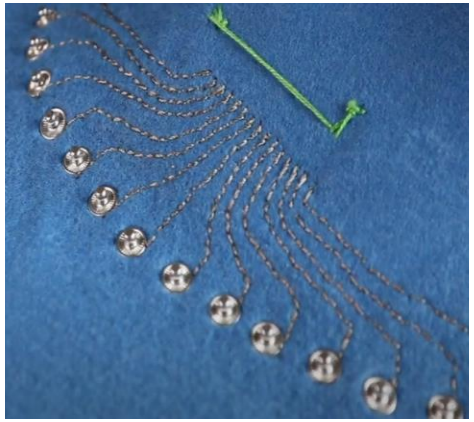
Source: Everactive report. available: https://cdn.everactive.com/content/uploads/2019/06/17103828/EverActive_Infograph_1.pdf
Source: IOT analytics report. Available: https://iot-analytics.com/wp/wp-content/uploads/2023/05/Insights-Release-State-of-IoT-2023-Number-of-connected-IoT-devices-growing-16-to-16.0-billion-globally.pdf

Background and Motivation

- **Energy can neither be created not destroyed.**
  - While breathing, walking, running, or any physical activities we expend energy.
  - What if we harness that energy ?



- **What if we have**
  - E-textile harvester ?
  - E-textile harvester acting as a sensor ?
  - Interfaced with CMOS chip embedded in-textile



Smart T-Shirt with Always-On Step Counting

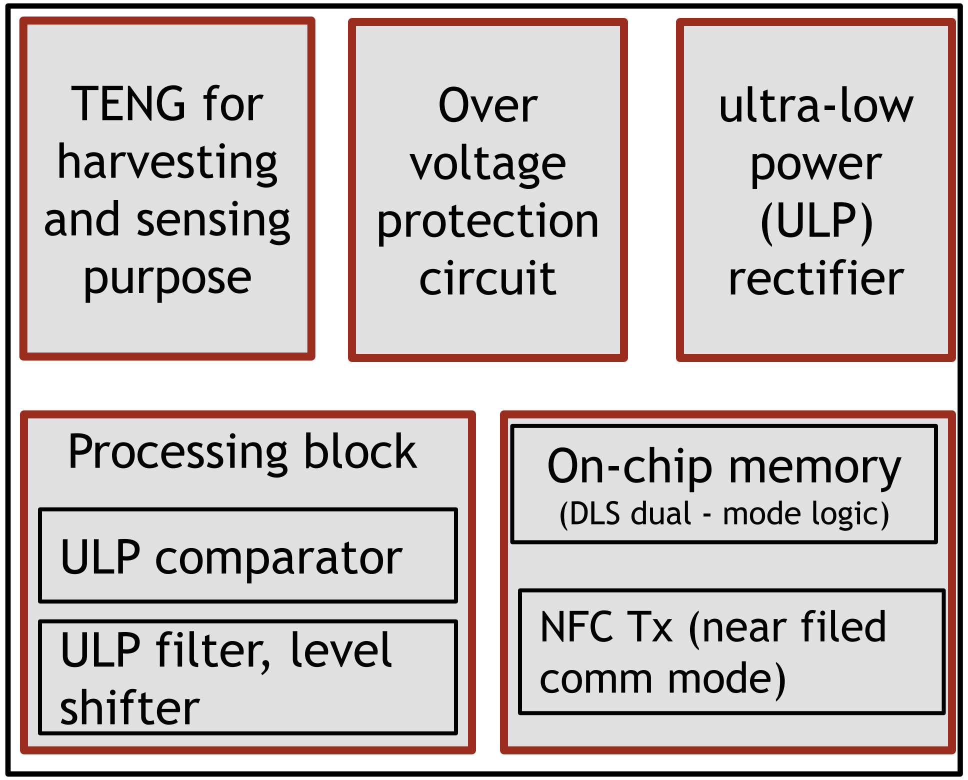
- We present, an always-on walking step counting system for e-textile applications
- Value proposition :
  - Powered by an in-textile Triboelectric nanogenerator (TENG)
  - True full system (sensing to communication)
  - Battery-less, inductor-less, No LDO, minimal off-chip components (~1mm size)
  - Minimal in-textile components (durability)
    - Dual-function TENG as harvester and sensor
  - Implemented in std CMOS for low cost (non-high voltage)

- **Requirements**
  - $E_{Consumed} < E_{Harvested}$
  - *pW level operation*

- **What can we do ?**
  - *E-textile for healthcare, Wellness monitoring, …*
  - *3D modelling for virtual tailoring*

Proposed Step Counting System Architecture

- Dual function TENG
  - Harvesting from walking naturally provides power when needed
  - Breathing sustains pW system power when no sensing needed
- EH-PMU
  - Harvester may produce high voltages
  - Over protection circuit for limiting voltage
  - ULP rectifier for VDD to the processing blocks

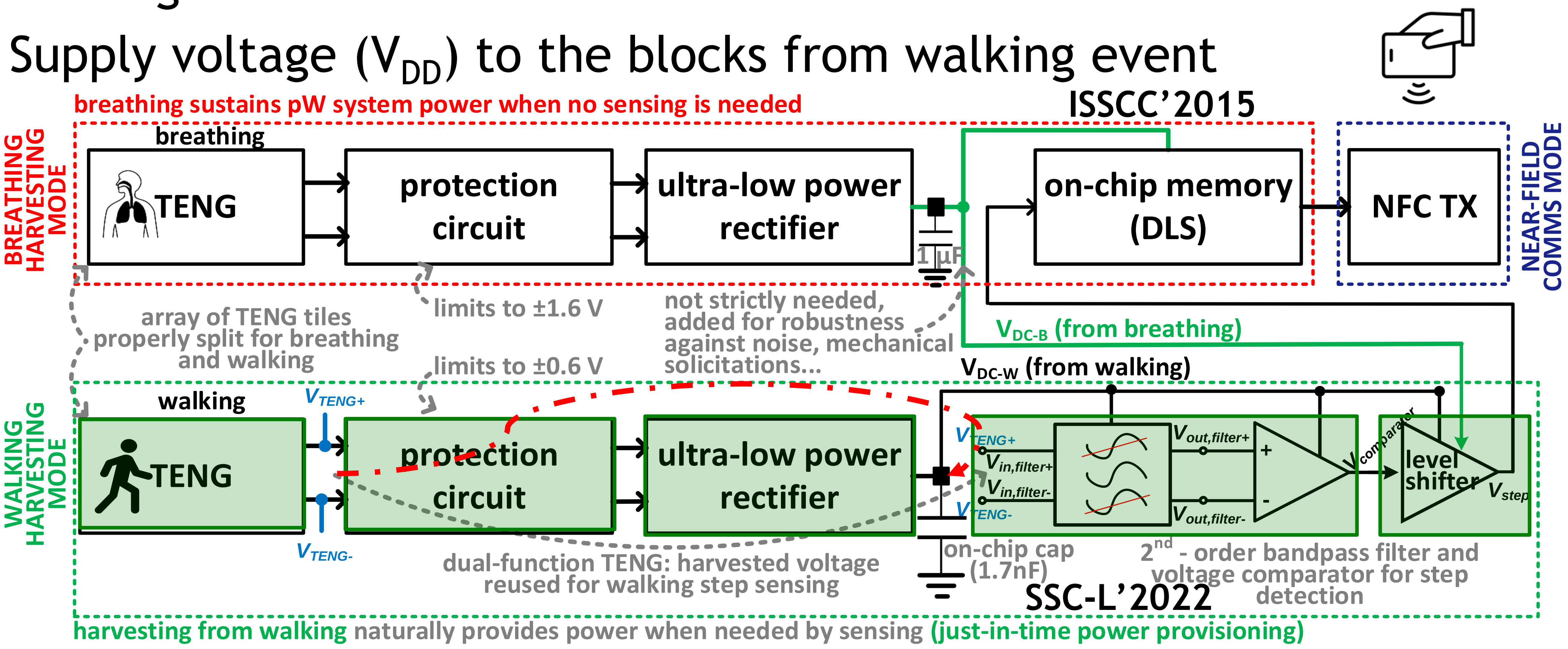


Features: <u>Battery less operation; Harvesting + Sensing + Step Counting + Storage, No LDO</u>

- Other Circuitry
  - Filtering and voltage comparison for step detection
  - Level shifters
- On-chip capacitor
  - Analog circuit functionality with human cadence
- Bondable capacitor
  - Breathing domain
- Storage and TX
  - DLS memory for storage
  - NFC TX

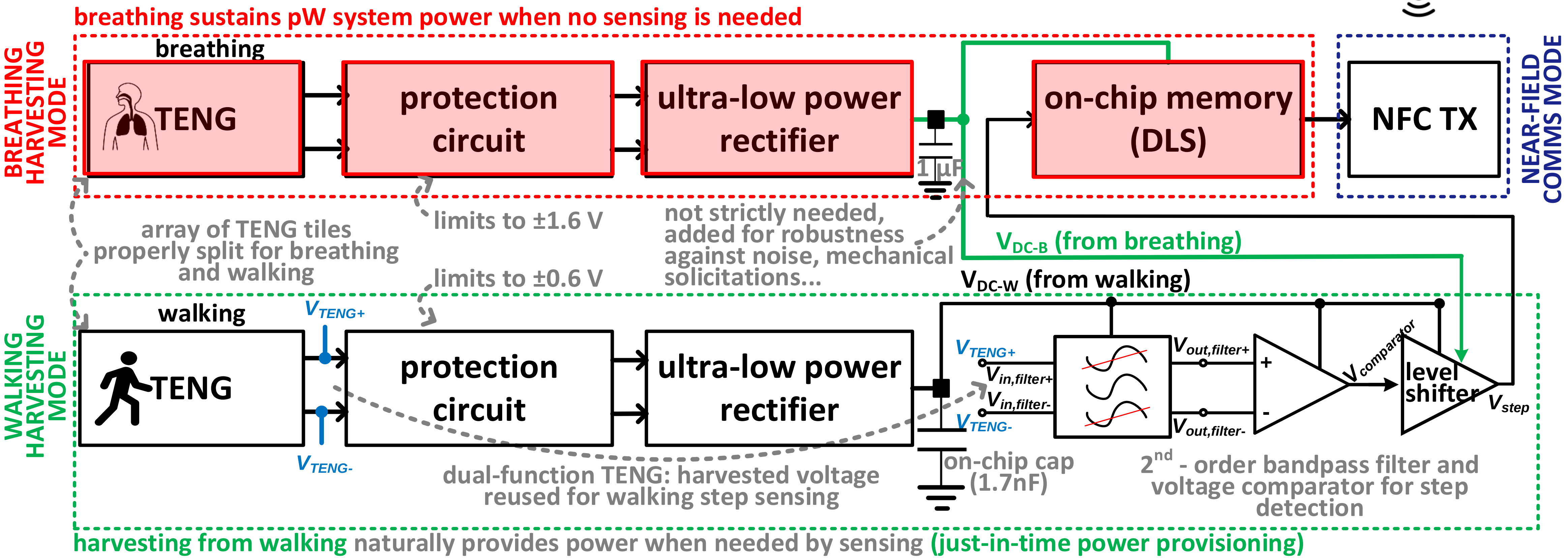
Proposed Step Counting System Architecture

- WALKING: 20-pw range (peak) power for just-in-time harvesting in walking event-drive activation
- Supply voltage (V_{DD}) to the blocks from walking event



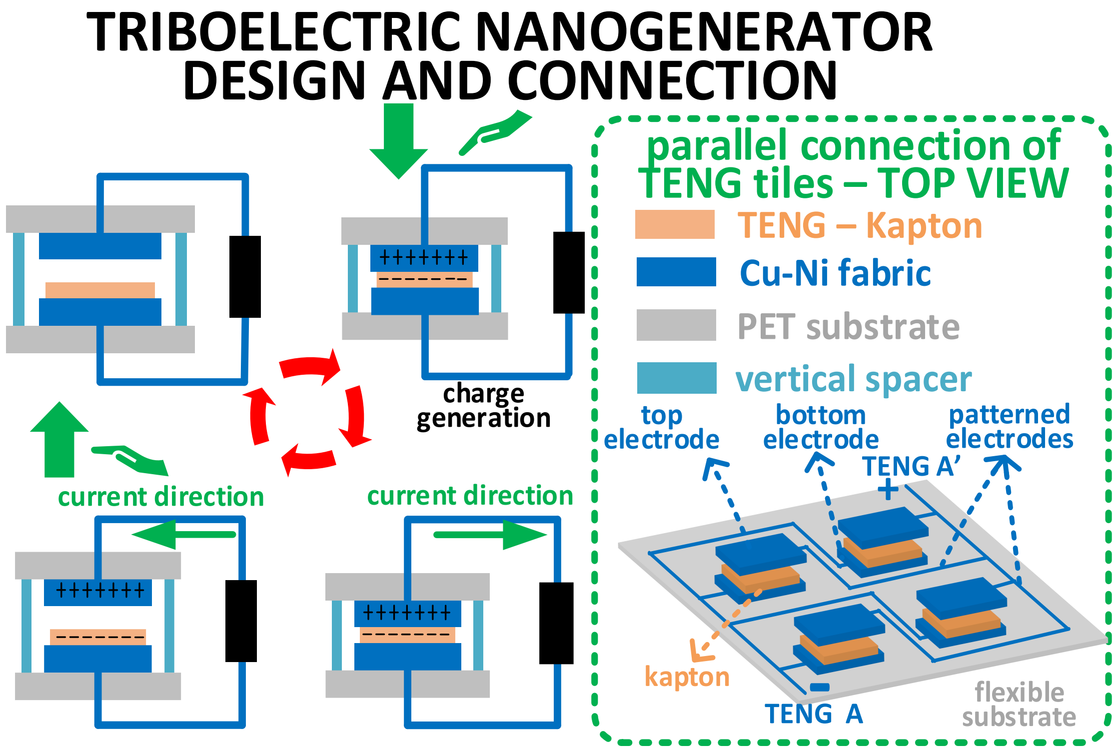
Proposed Step Counting System Architecture

- BREATHING: pw-range power + lowest f_{min} <0.1Hz for always-on basic functions, even with minuscule kinetic power from breathing
- Supply voltage (V_{DD}) to the blocks from breathing event



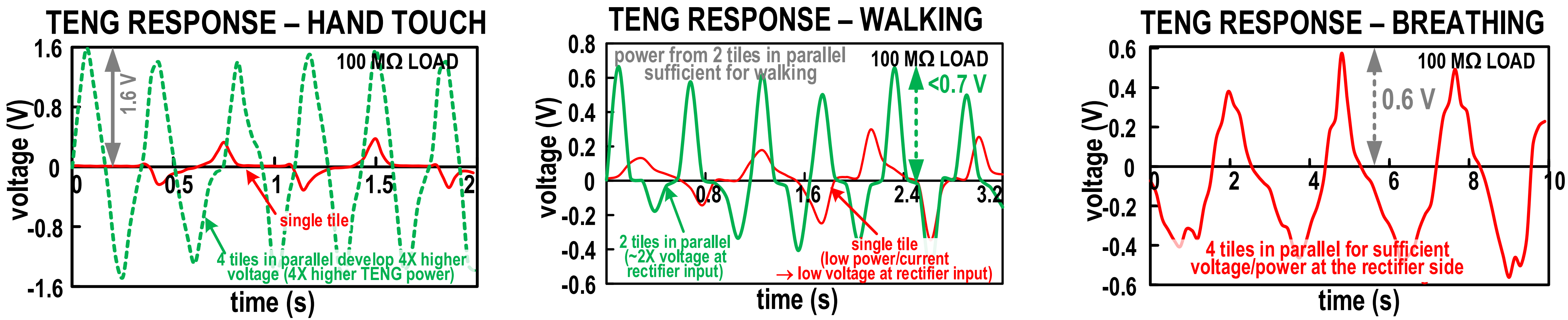
Characterization of TENG (1)

- In-house designed TENG
  - Kapton and Cu-Ni material -> weak triboelectrification to keep voltage lower than ~3.3V
  - Patterned in a tiled fashion – 2cm * 2cm
  - Total in-textile area ~25cm^2
  - Same TENG is reused for sensing and harvesting

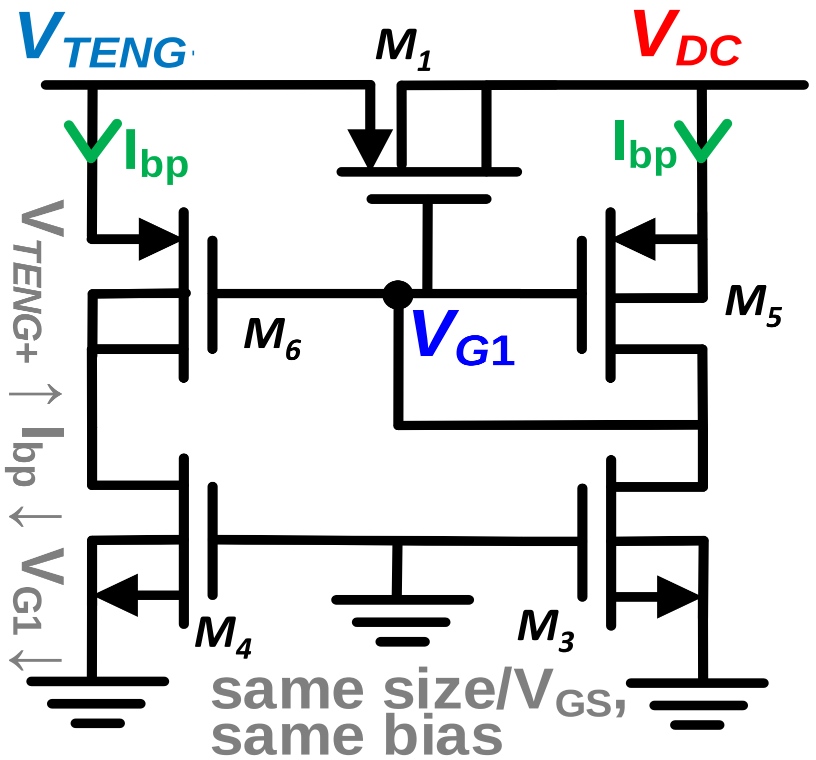


Characterization of TENG (2)

- Measurements of the TENG for various activities – transient response
  - nominal hand touch, walking, and breathing
  - NO sufficient energy from single tile
  - 2 tiles in parallel -> sufficient for detecting walking
  - Minimum energy harvested from breathing
    - 4 tiles in parallel for sufficient power/voltage at rectifier side



Operation of the ULP Rectifier (1)



Voltage V_{TENG} rises

M_1 turns on and V_{DC} increases

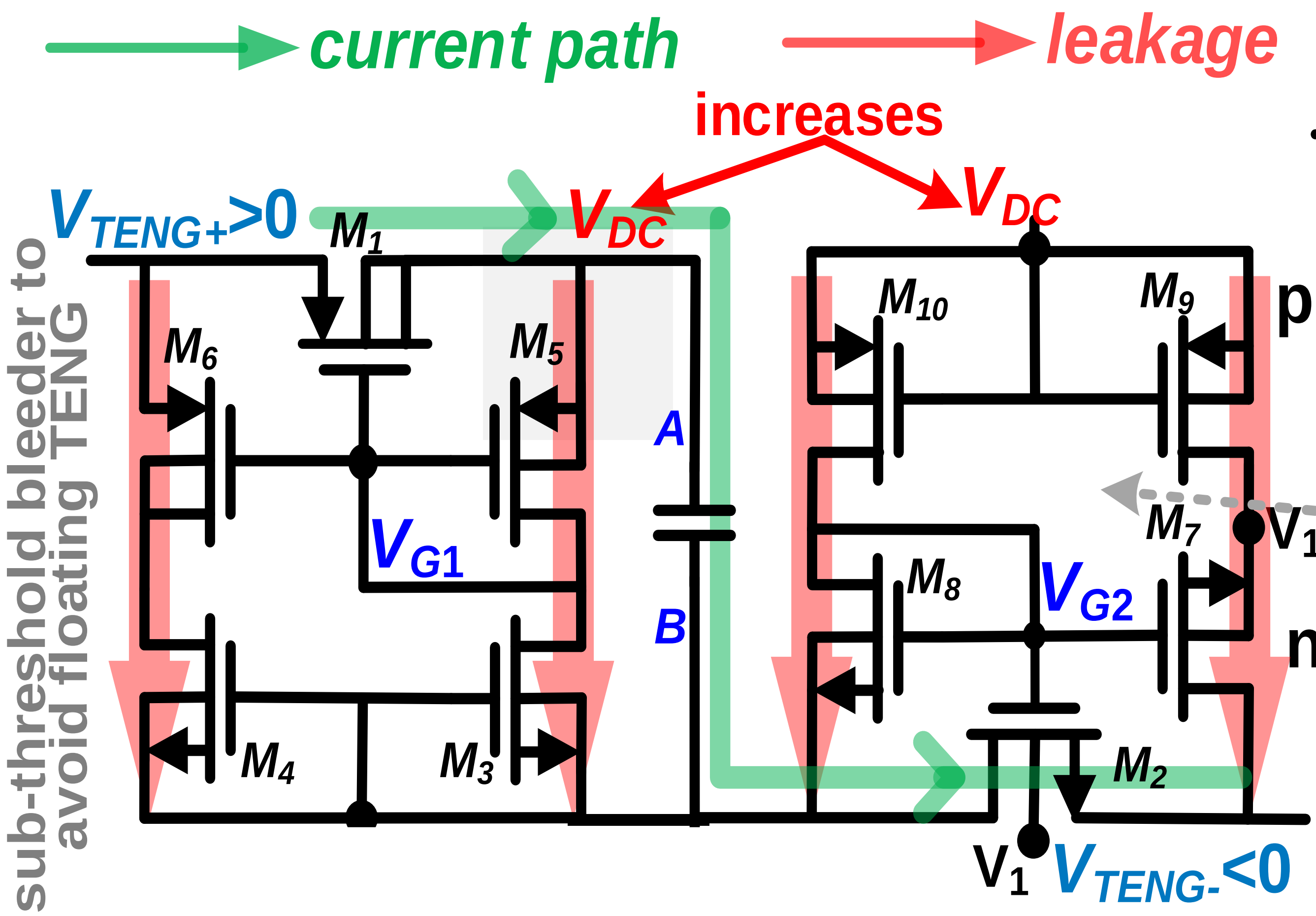
Current through M_5 increases

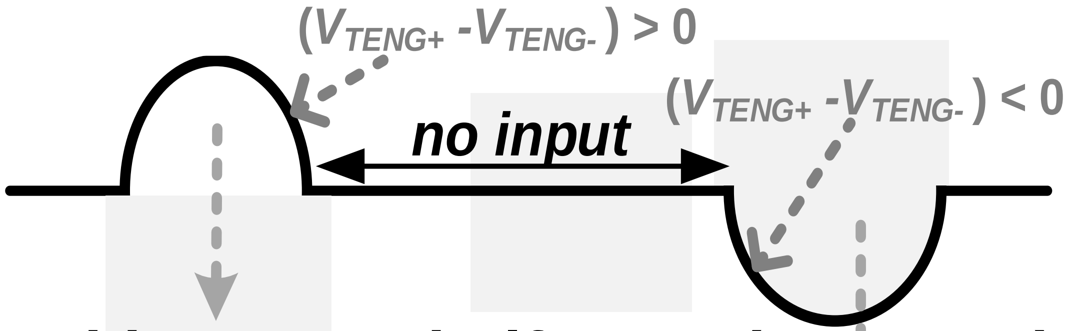
Voltage V_{G1} rises and M1 into super-cutoff

- Full bridge active rectifier
  - formed with this block and its duality.
  - OFF current well below the regular transistor leakage.
  - M_3/M_4 are in super cutoff region of operation.

Opposite considerations for other half circuit

Operation of the ULP Rectifier (2)





positive TENG half-wave (pressure)

- when V_{TENG+} increases, V_{G1} increases
- after V_{TENG+} peaks, M1 turns off

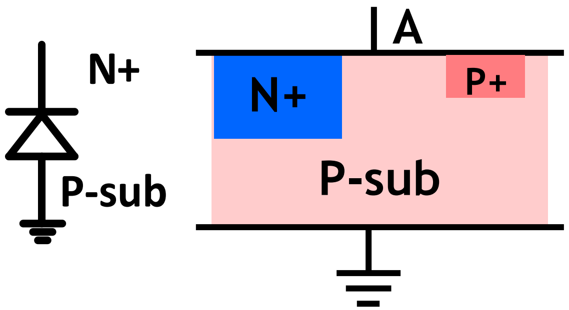
(opposite considerations)

negative TENG half-wave (release)

- $(V_{TENG+} - V_{TENG-}) < 0$
- opposite behavior (reverse all currents)

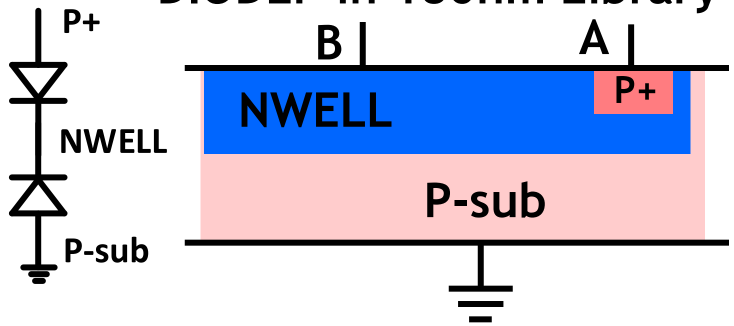
Over Protection Circuit - Analysis

DIODEN in 180nm Library



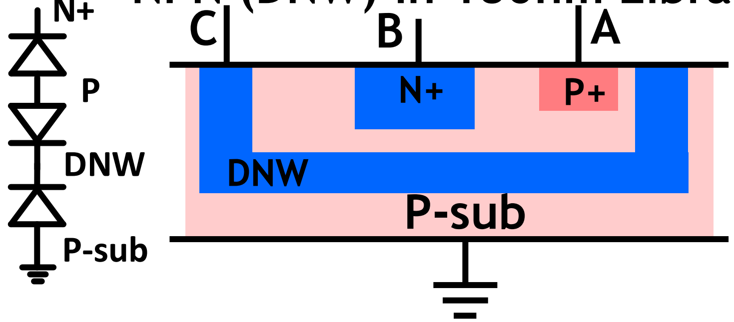
CAN ONLY CLAMP +VE WAVE

DIODEP in 180nm Library



CAN ONLY CLAMP +VE WAVE

NPN (DNW) in 180nm Library

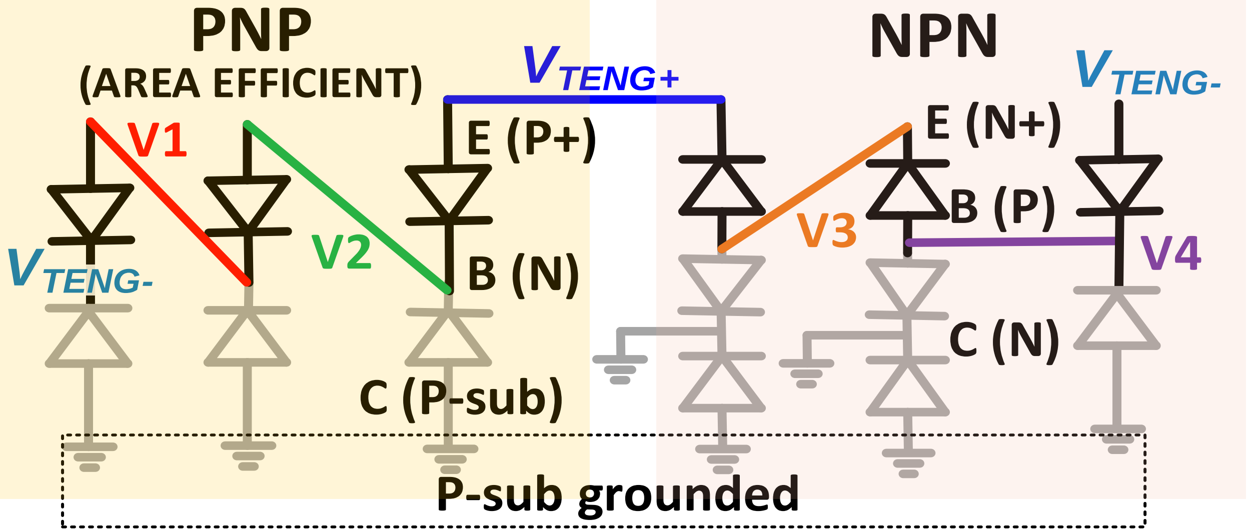


CAN CLAMP +VE AND -VE WAVE

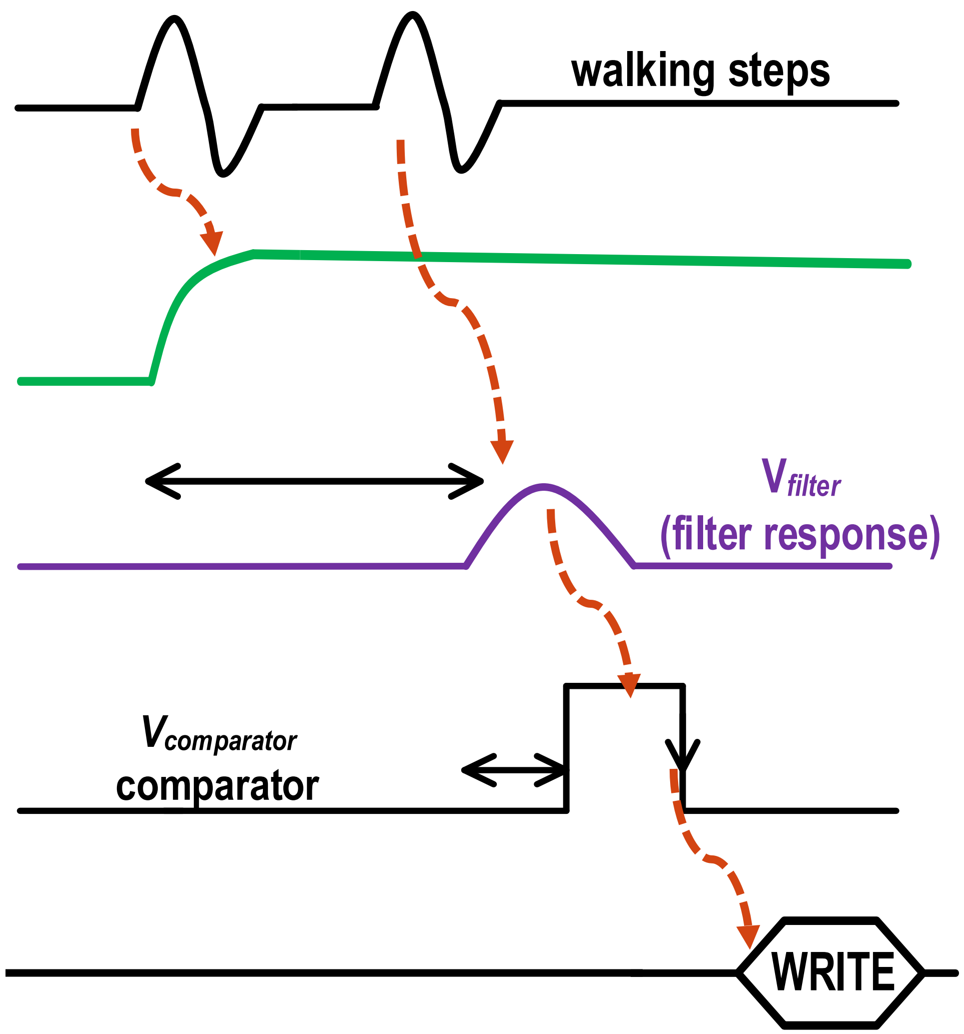
PROPOSED OVER PROTECTION CIRCUIT

2-PNP & DIODEN

2-NPN & DIODEN

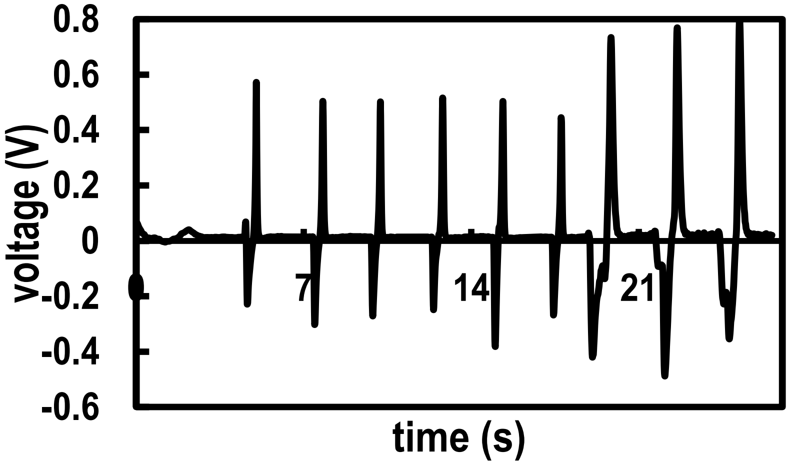


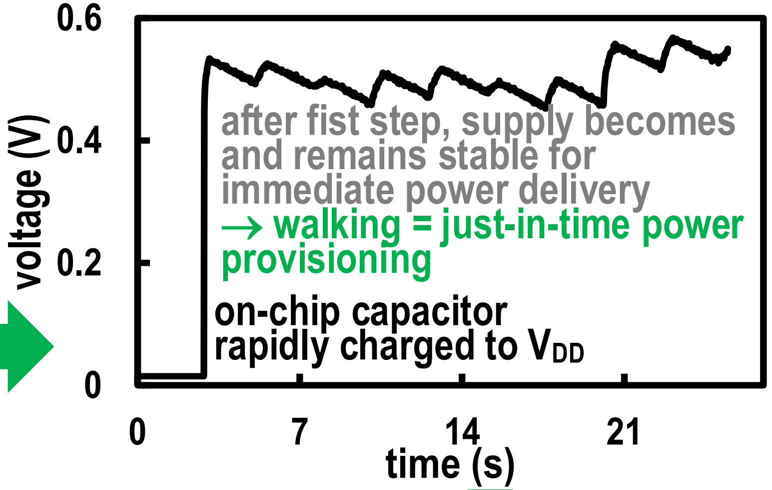
System Response - Walking Step Event

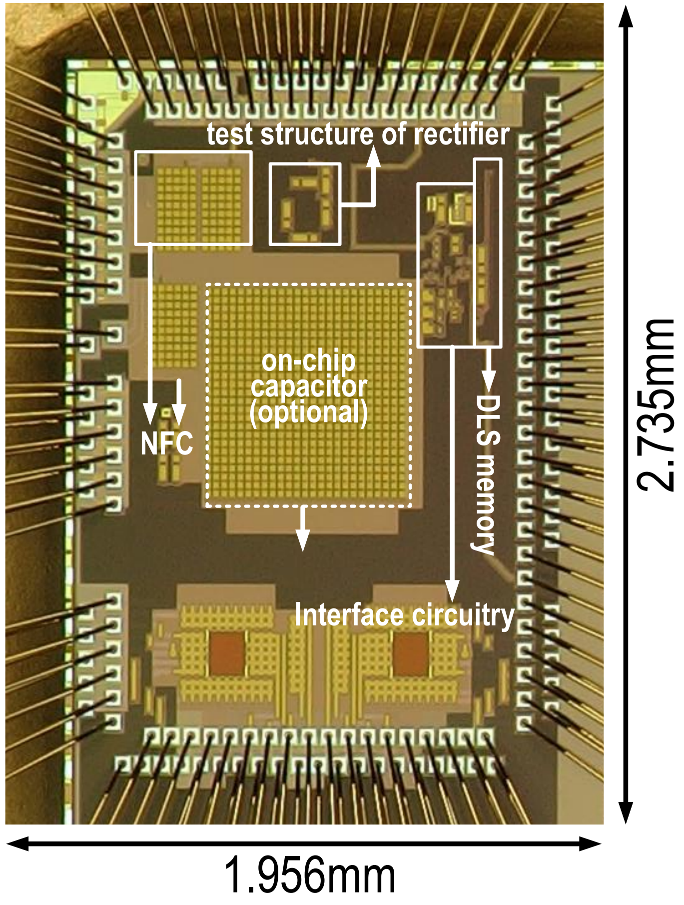


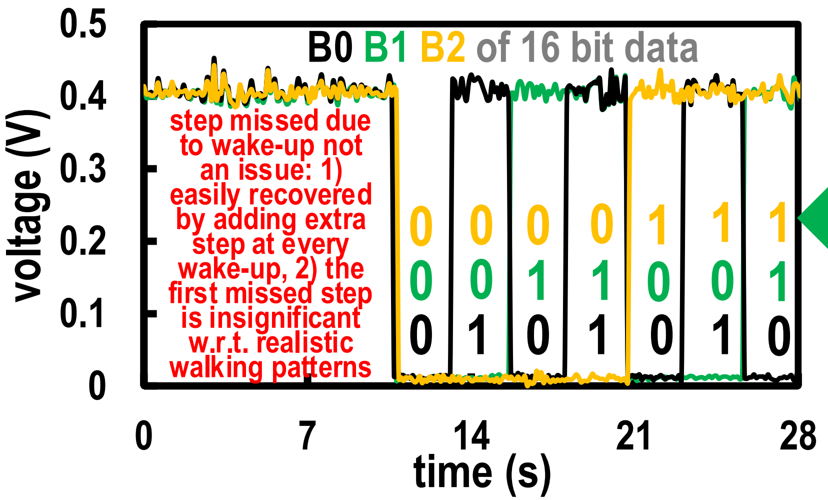
1. Transient response of the TENG due to walking;
2. Voltage after the rectifier ($V_{rectifier}$);
3. Response of the analog filter for the walking events. step-missed due to wakeup;
4. Response of the comparator;
5. Data written to the DLS memory during negative edge;

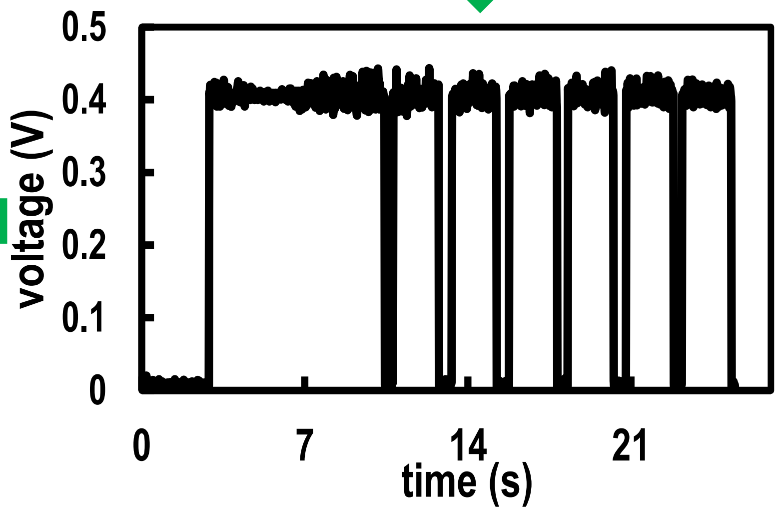
Testchip and System Measurements







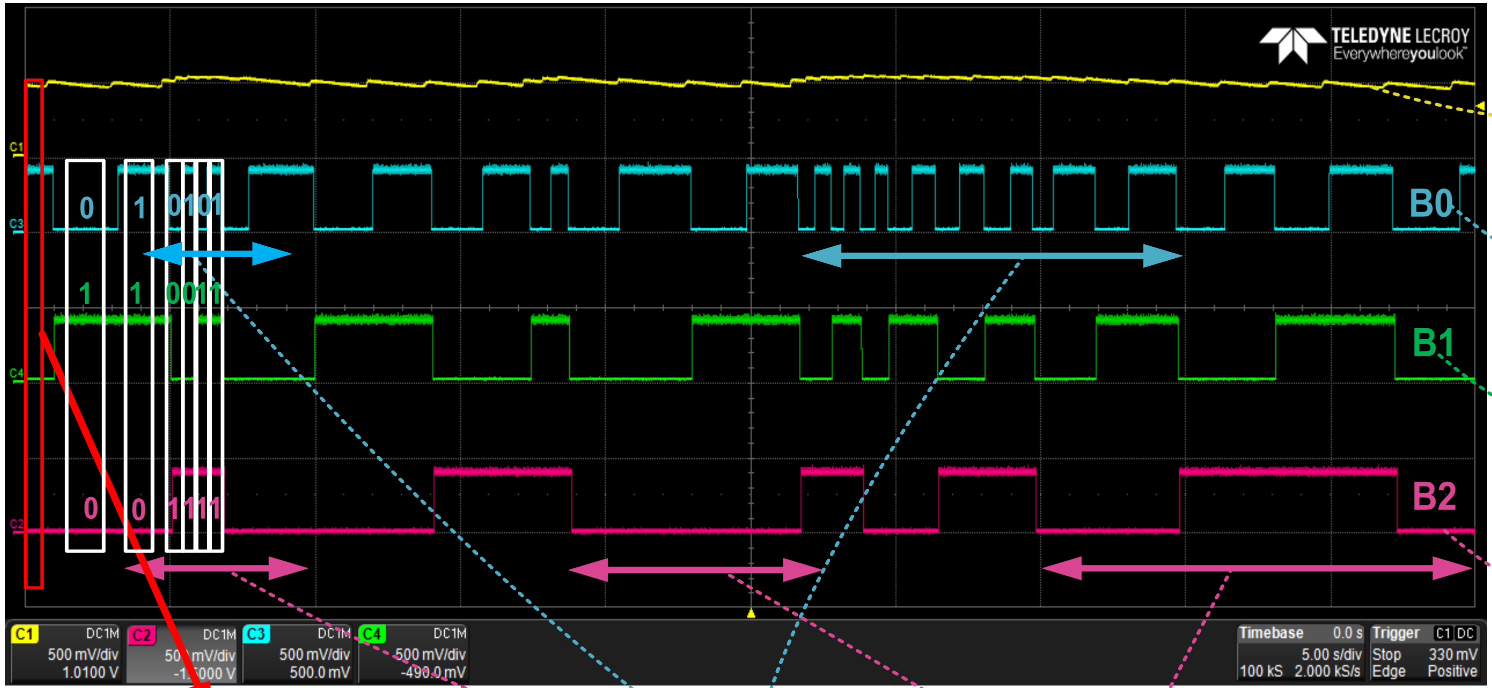




- Fabricated in TSMC 180nm process

System Functionality for Various Activities

First 3 bits of 16 bit DLS counter is depicted along with the rectified voltage



voltage across the capacitor stored at the output of the rectifier

first bit of 16 bit DLS memory

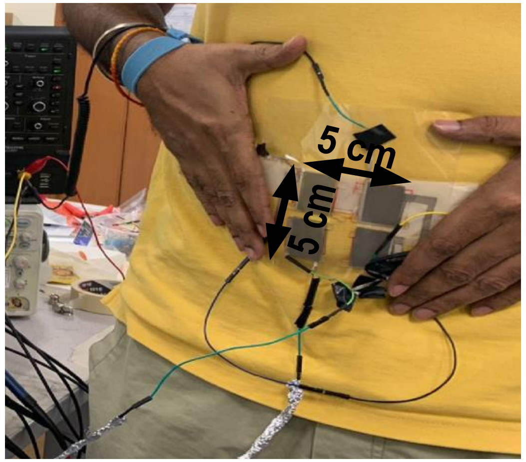
second bit of 16 bit DLS memory

third bit of 16 bit DLS memory

Initial state of B0, B1, and B2 of the DLS memory

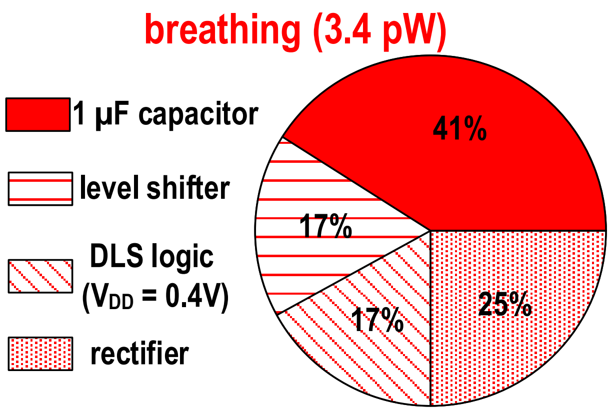
fast walking

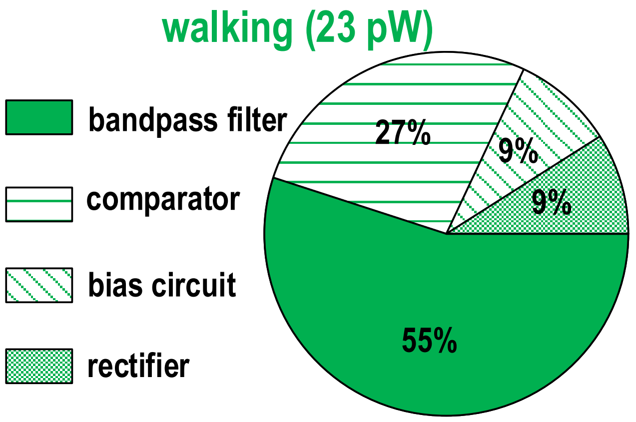
slow walking

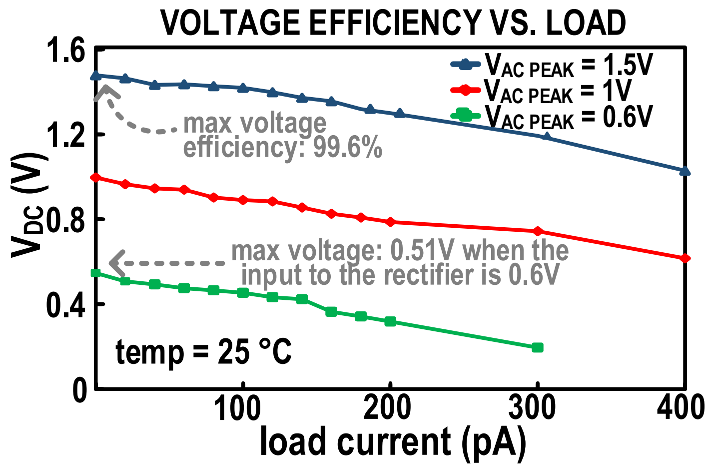


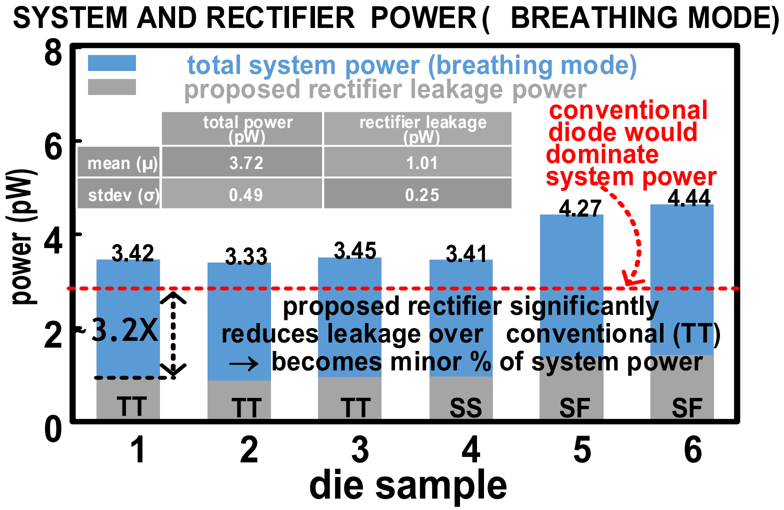
- response of the system is monitored for walking at random speed
- shown here is response after the system start-up
- total 40 steps with no steps missing

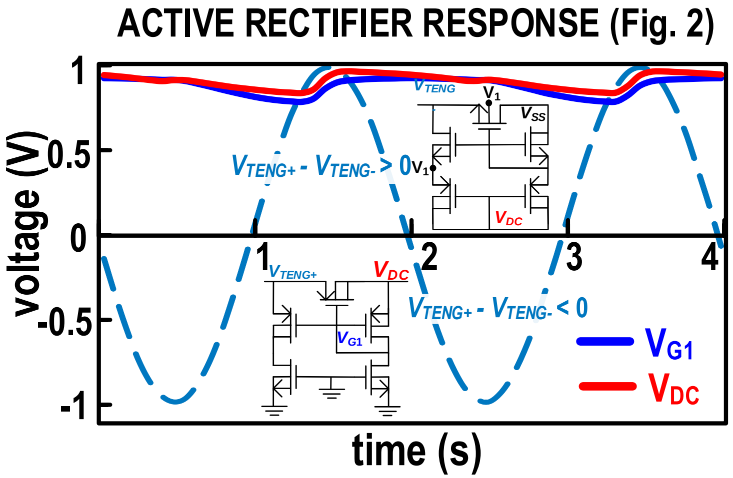
System Measurements

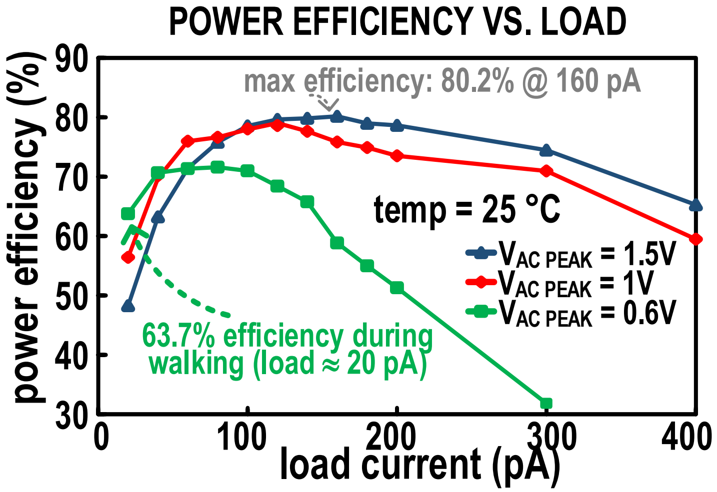




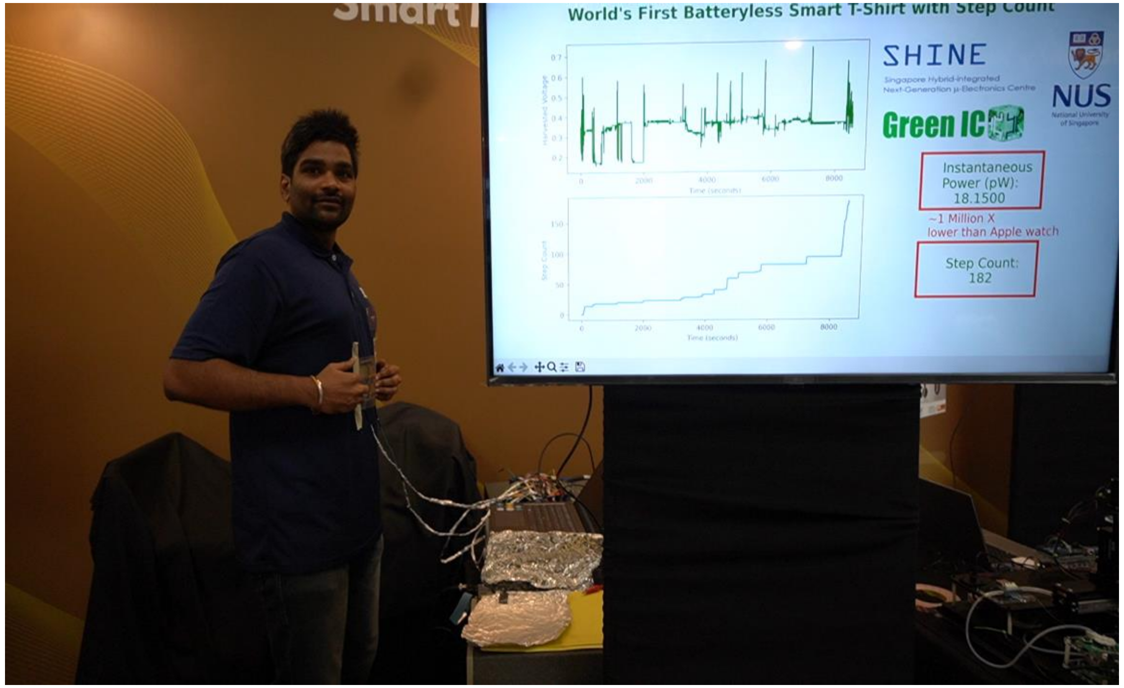


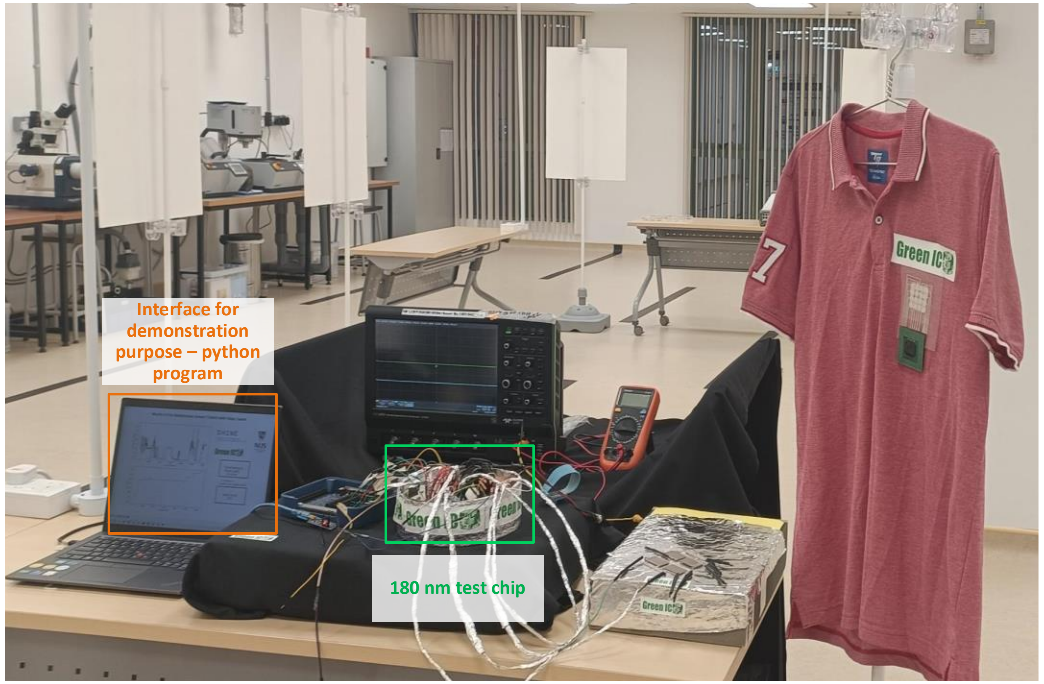






Setup for the Demonstration





Advancing the State of the Art

	This work	JSSC'21 [2]	JSSC'19 [3]	JSSC'21 [4]	ISSCC'13 [1]	ISSCC'19 [5]	ISSCC'18 [6]
technology (nm)	180	180	180 BCD (HV)	180 BCD (HV)	180	350	40
area (mm^2)	0.36 core + 0.68 cap (die-stackable)	0.81	5.91	1.69	1.46	1.9	0.55
type of system	**step counter w/ harvesting from breathing / walking / motion**	body temperature monitor	harvesting sub-system	harvesting sub-system (vibration)	e-textile body area network	harvesting sub-system (multi-axial motion)	harvesting sub-system (vibration)
energy harvester and substrate	low-voltage triboelectric (<3.3 V) e-textile substrate	triboelectric (4 V) flexible substrate	triboelectric (130 V)	triboelectric (36 V) rigid substrate	inductive RF	piezo-electric (1.6 V) rigid substrate	piezo-electric (6 V) rigid substrate
total power consumption (mode)	3.4 pW (breathing mode) 23 pW (walking sensing)	17.01 nW (temp. sensing) 5.21 nW (PMU)	N/A (harvesting only)	N/A harvesting only)	2.9 mW (data transmission)	N/A (harvesting only)	N/A (harvesting only)
voltage before rectifier (V)	$\leq$3.3 V_{pp}	4 V_{pp}	130 V_{pp}	36 V_{pp}	2 (after rectifier)	1.6 V_{pp}	6 V_{pp}
harvesting efficiency (mode)	63.7% (peak 80.2%)	N/A	70.7%	75.6% (harvesting mode)	N/A	84.6% (harvesting mode)	94% (harvesting mode)
sensing accuracy	>98% (step counting)	±1 °C (temp.)	N/A	N/A	N/A	N/A	N/A

triboelectric

piezo-electric

min. power

Advancing the State of the Art

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technology (nm)	180	180	180 BCD (HV)	180 BCD (HV)	180	350	40
max energy retention (storage cap)	16 minutes (>> respiratory period)	10 s	N/A	24.7 s*	N/A	11.5 min*	~0.2 s*
cold start-up voltage (V)	0.4	0.6	N/A	2.8	N/A	1.5	1.5
power extraction improvement FOM [6]**	~442	N/A	314	N/A	NA	511	420
min. harvesting frequency	<0.1 Hz (breathing, human motion)	1 Hz (human motion, no breathing)	250 Hz (vibration, no human motion)	55 Hz (vibration, no human motion)	27 MHz (from inductive RF)	90 Hz (vibration, rare/sudden human motion)	75 Hz (vibration, no human motion)
full-system demo	YES (in-textile)	NO	NO	NO	NO	NO	NO
sub-system coverage	harvester+ sensing+processing+ MEM+NFC comms	harvester + on-chip rectifier/ sensor	harvester + multi-die stacking harvesting	harvester + on-chip harvesting	harvester + on-chip harv./ comms + off-chip AFE	harvester + on-chip harvesting	harvester + on-chip harvesting
off-chip components	1 bondable cap (1 µF, <1 mm^2, stackable on main die)	storage capacitors, digital sub-system	inductor (10 mH), battery	rectifier, inductor, 100 V capacitors, battery	AFE	large inductor, capacitors (total 57 µF)	large inductor, capacitors (total 110 µF)

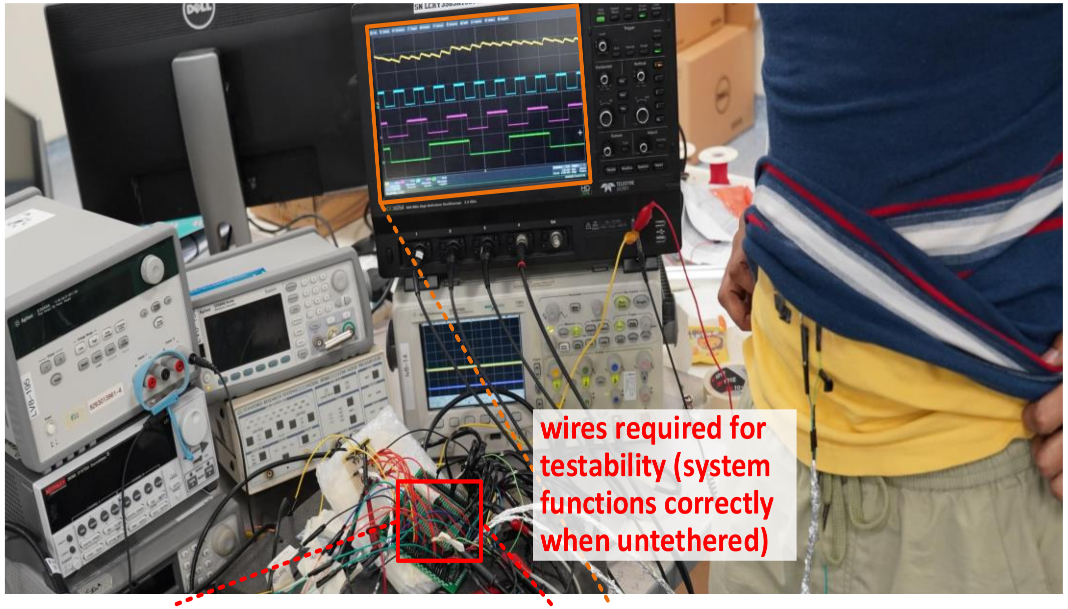
full system demonstration

sub-system(s) only

* calculated from paper

Conclusion

- Power as key system interaction dimension
- Record-breaking power reductions and enablement of brand-new capabilities
  - pw range : smart T-shirt with always-on step counting (no battery, inductors..) for conformability and low cost
  - Lowest power and f_{min} : 23pW (1.4pW) walking (retention), <0.1 Hz
  - >230X better than prior partial system demo reporting power.



Acknowledgments

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- The authors would like to thank Mr. Feng Zheng and Prof. Lee Pooi See, NTU – Singapore

- Green IC Research Group!

Thank You!

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[2] J. S. Y. Tan, J. H. Park, J. Li, Y. Dong, K. H. Chan, G. W. Ho, and J. Yoo, "A Fully Energy-Autonomous Temperature-to-Time Converter Powered by a Triboelectric Energy Harvester for Biomedical Applications," *IEEE Journal of Solid-State Circuits*, vol. 56, no. 10, pp. 2913-2923, Oct.2021.

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[6] A. Quelen, A. More, P. Gasnier, R. Grezaud, S. Monfray, and G. Pillonnet, "A 30nA quiescent 80nW-to-14mW power-range shock-optimized SECE-based piezoelectric harvesting interface with 420% harvested-energy improvement," *IEEE International Solid-State Circuits Conference*, pp. 150-152, Feb. 2018.

Miscellaneous

Triboelectric Material Series

- All materials including metals, polymers, wood, and semiconductors… exhibits triboelectric effect.
- Depends on the strength of triboelectrification.

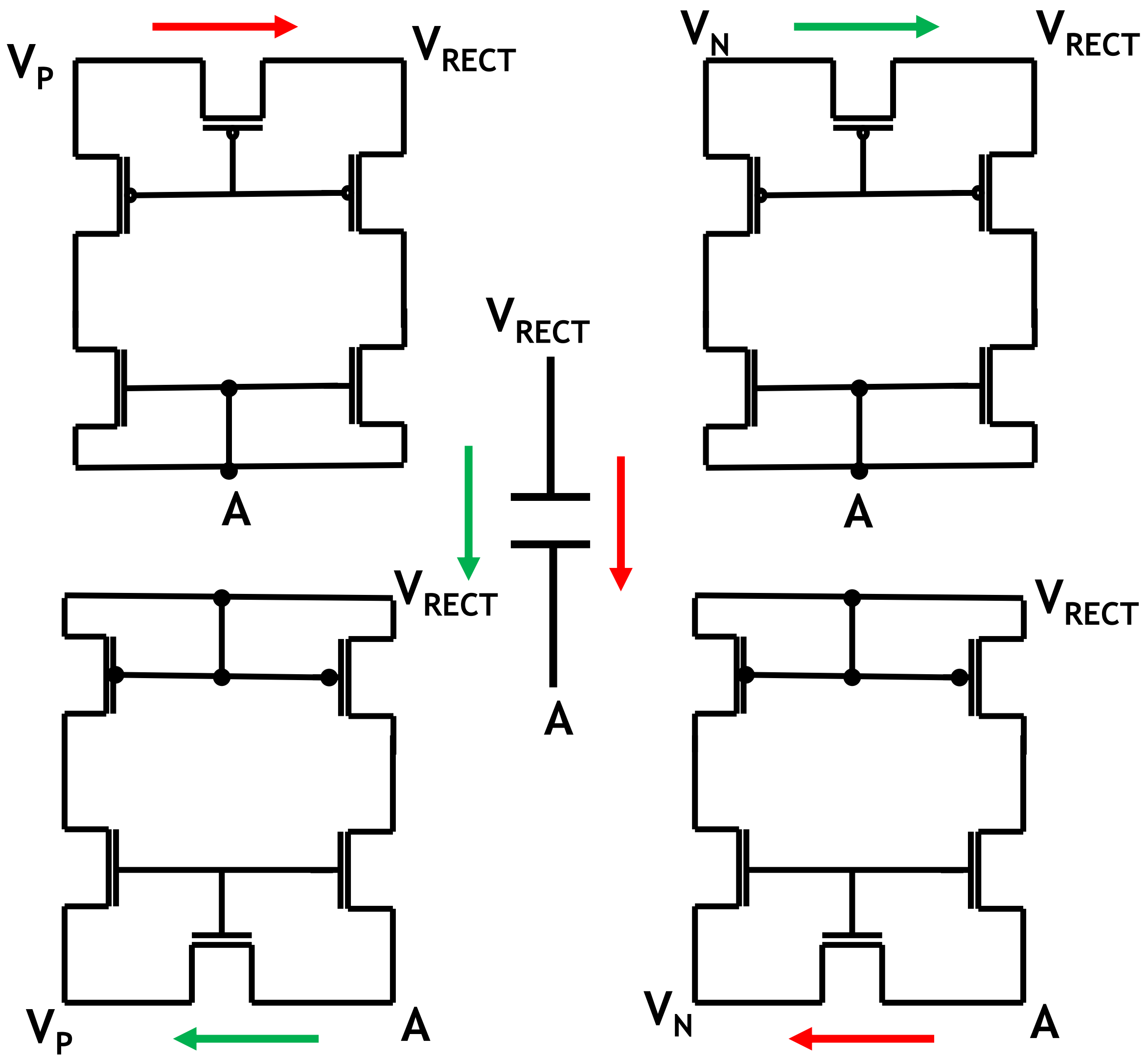
Easily looses electrons	Easily gains electrons
Polyformaldehyde	Polyester
Etylcellulose	Polyisobutylene
Polyamide 11	Polyurethane flexible sponge
Polyamide 6-6	Polyethylene terephthalate
Melamine formal	Polychlorobutadine
Wool, Knitted	Butadiene-acrylonitrile copolymer
Silk, Woven	Nature rubber
Aluminum	Polyacrylonitrile
Paper	Polychloroether
Cotton	Polyvinylidene chloride
Steel	Polystyrene
Wood	Polypropylene
Hard rubber	Polydiphenyl propane carbonate
Nickle-Copper	Kapton
Sulfur	PVC
Brass, Silver	Polytrifluorochloroethylene
Polymethyl methacrylate	Teflon

Positive

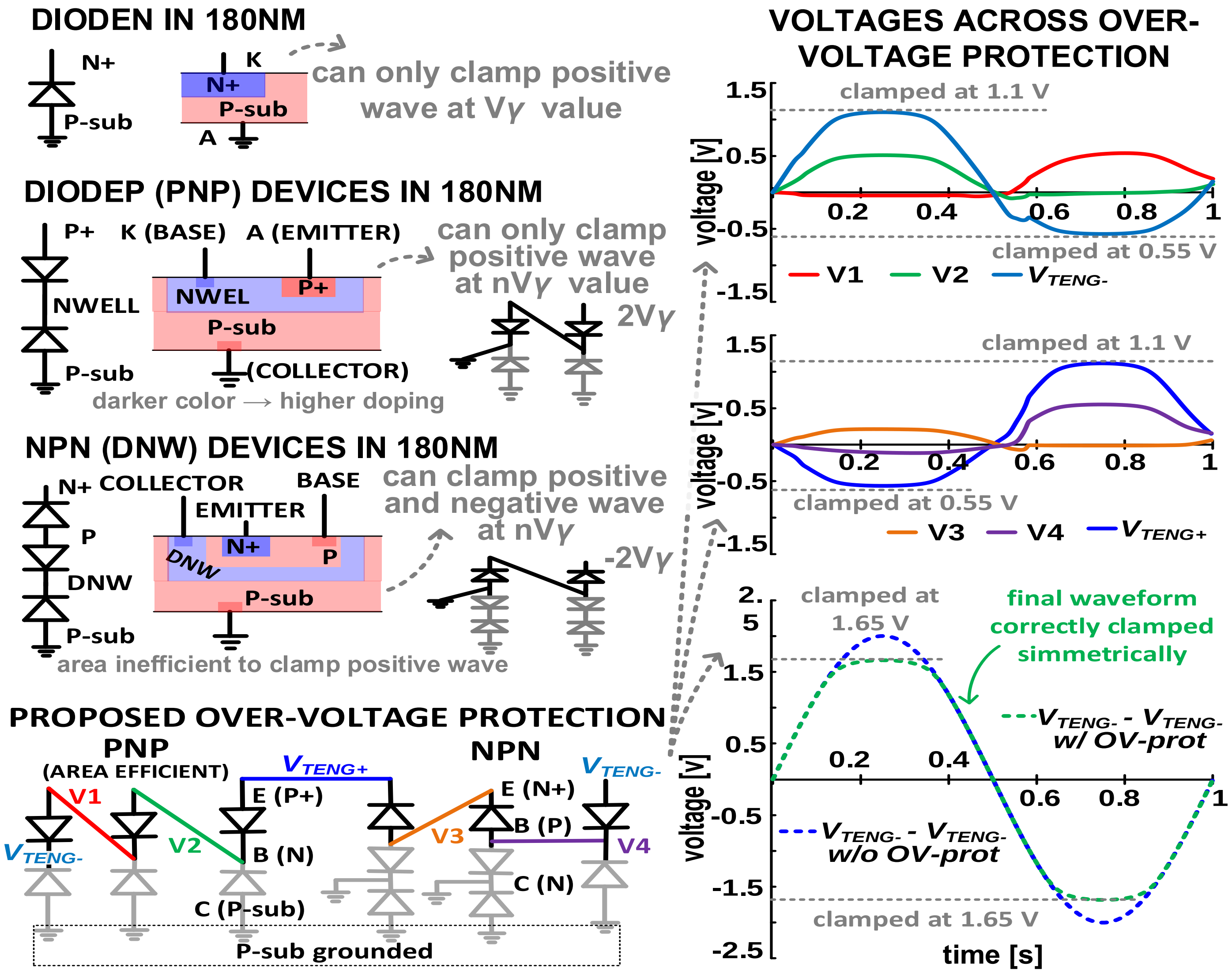
Negative

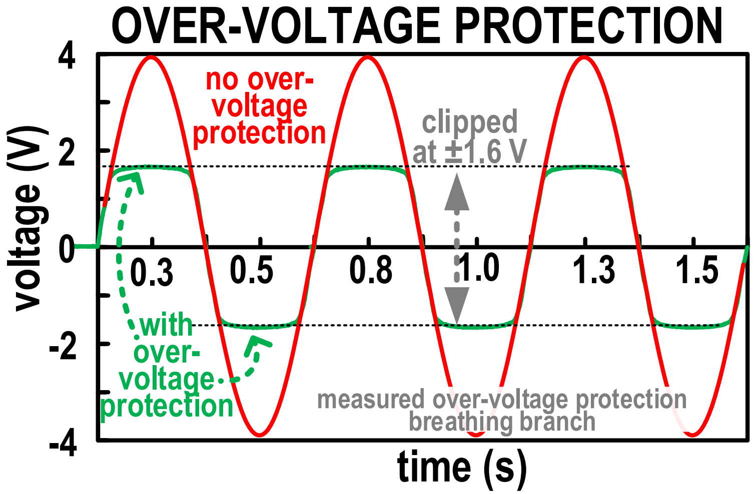
Operation of the ULP rectifier

- Full bridge active rectifier
  - formed with this block and its duality.
  - OFF current well below the regular transistor leakage.
  - Devices are in super cutoff region of operation.



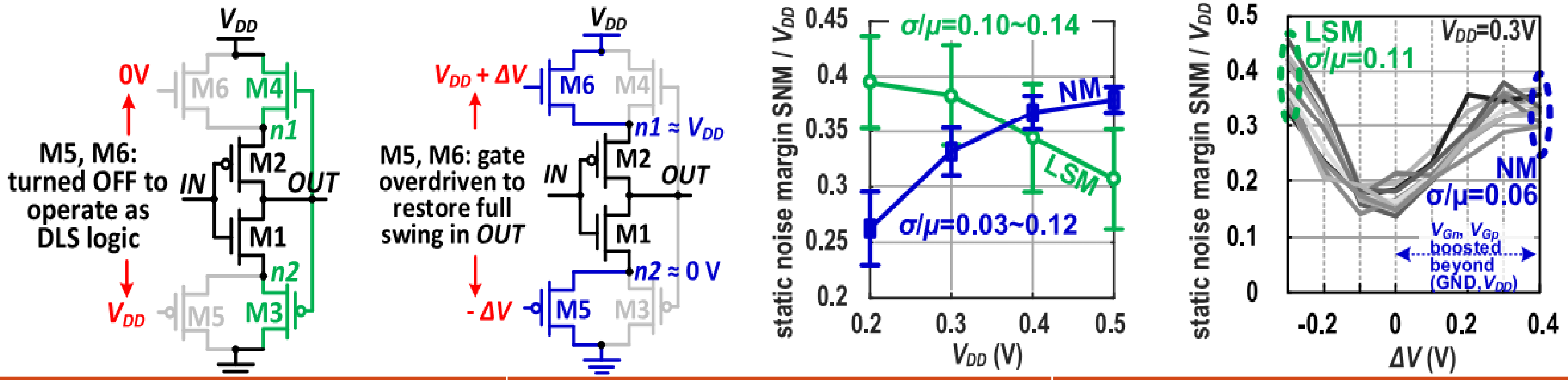
Over Protection Circuit – Detailed Analysis





- Measure transient waveform of the over-voltage protection circuit

Dual Mode Logic



V_{DD} (V)	Noise Margin (mV)	TYPE
0.5	~187	Dual Mode Logic (DML)
0.4	~144	Dual Mode Logic (DML)
0.3	~99	Dual Mode Logic (DML)
0.2	~51	Dual Mode Logic (DML)

[7] L. Lin, S. Jain and M. Alioto, "Sub-nW Microcontroller With Dual-Mode Logic and Self-Startup for Battery-Indifferent Sensor Nodes," in *IEEE Journal of Solid-State Circuits*, vol. 56, no. 5, pp. 1618-1629, May 2021

Harvesting Energy - TENG

Area	Walking	Breathing
2cm*2cm	~248 pJ	~100 pJ

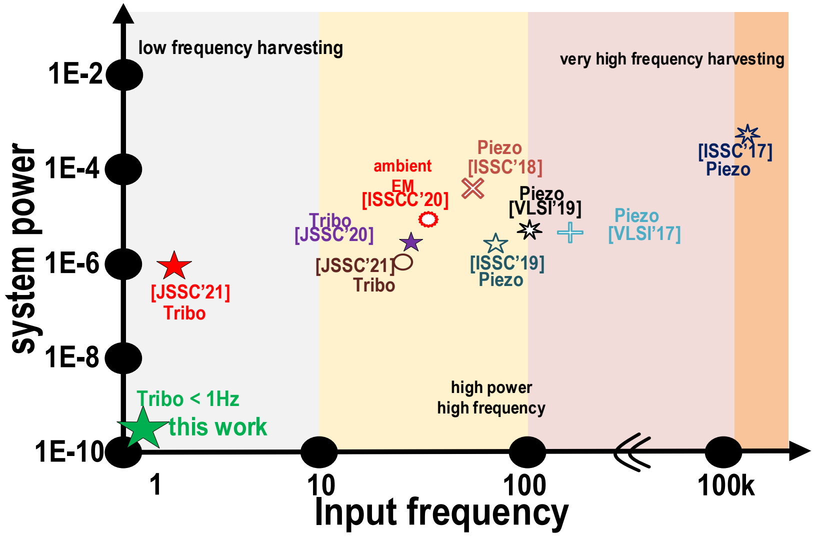
TENG :

Kapton Material
Cu-Ni Electrode

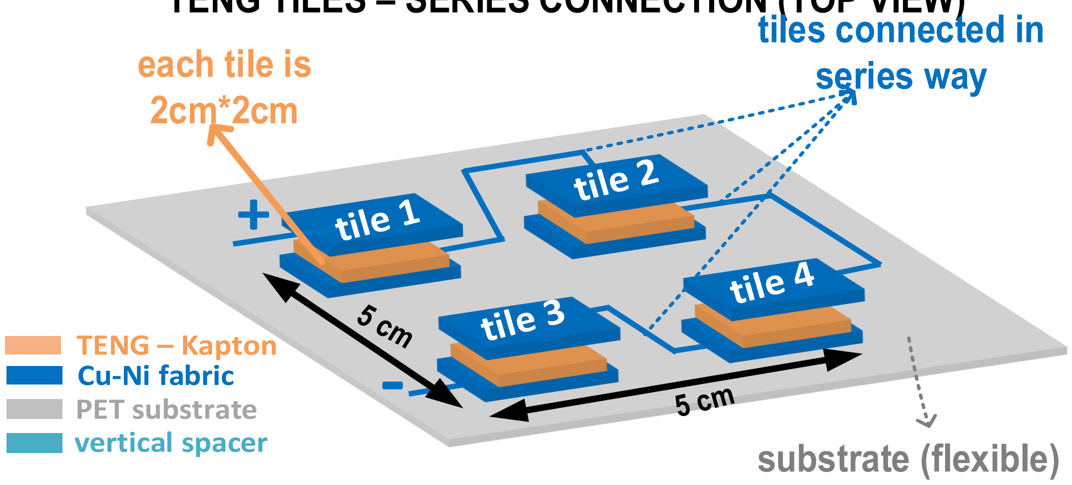
Energy Source	Power Density	Frequency	Characteristics
Solar/PV	10 – 15 μW/cm²	DC	Exposure to light
RF Energy	0.1 μW/cm²	380M – 5 Hz	
Thermal – body heat	40 μW/cm²	DC	High temperature difference
Piezo	4 μW/cm²	> 30 Hz	
TENG	1 μW/cm²	< 5 Hz	

TENG Analysis

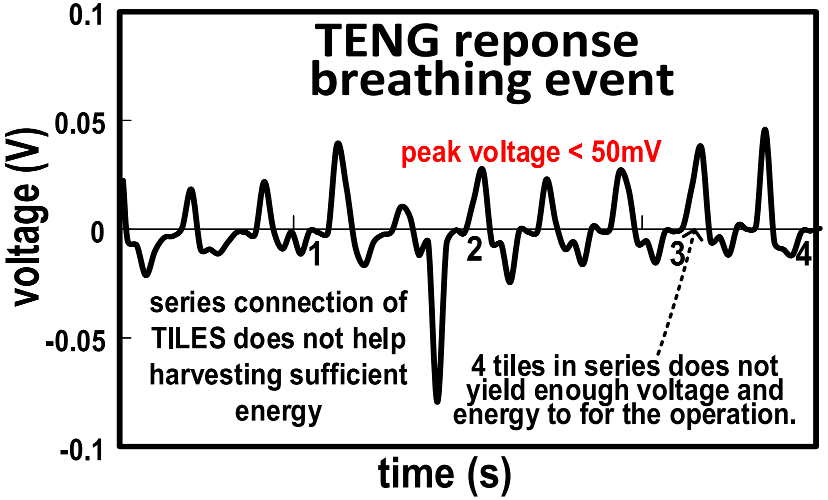
LITERATURE



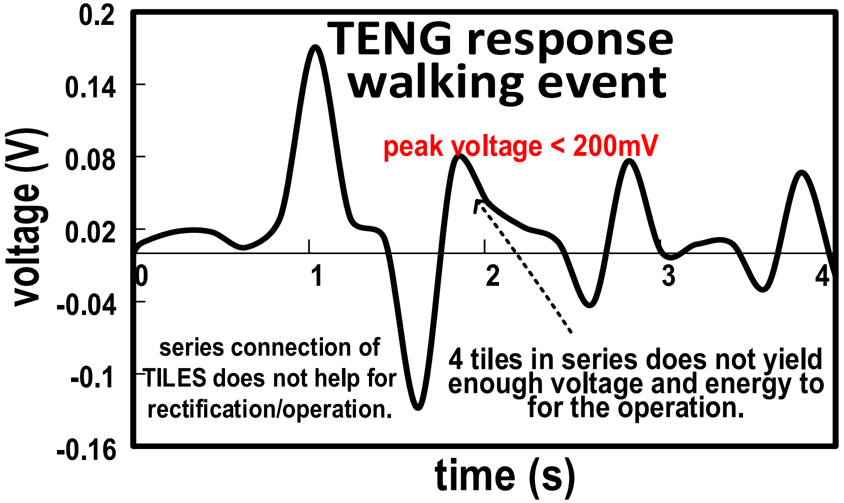
TENG TILES – SERIES CONNECTION (TOP VIEW)



SERIES CONNECTION OF TENG – 4 TILES



SERIES CONNECTION OF TENG – 4 TILES

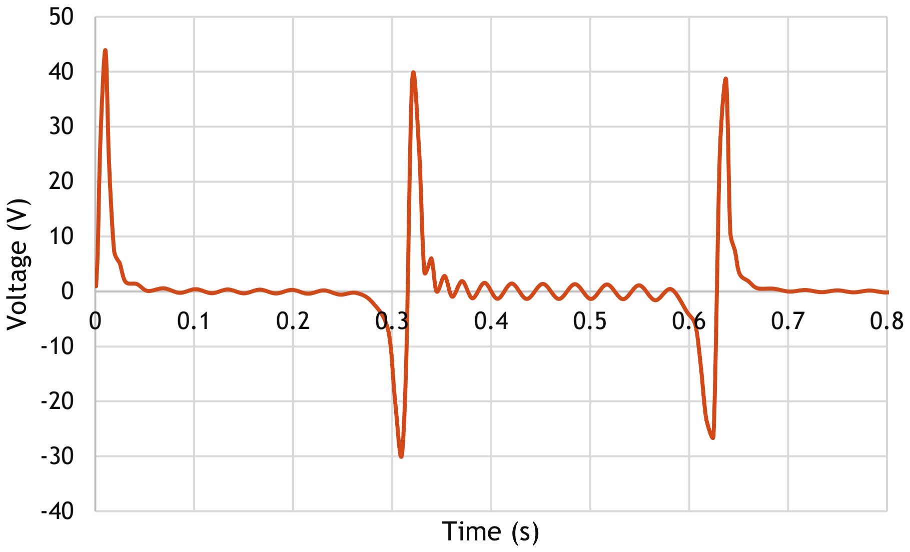


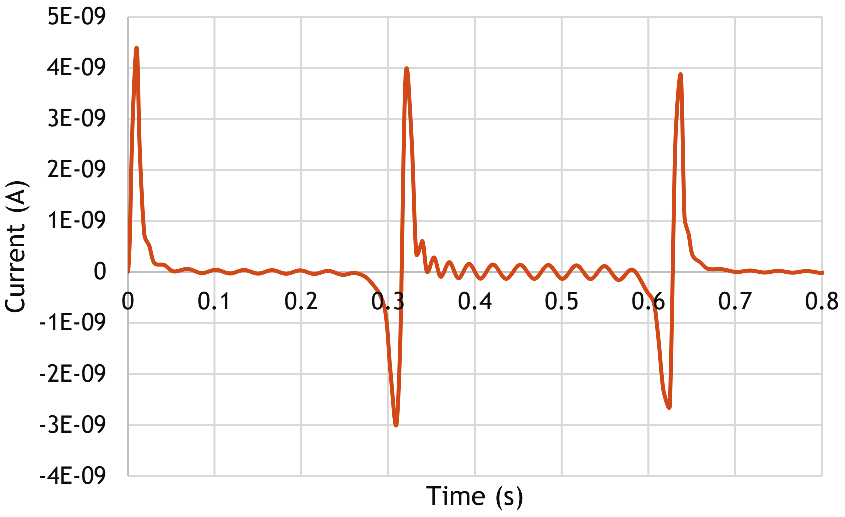
TENG Analysis

➢ Circuit Simulations and Measurements:

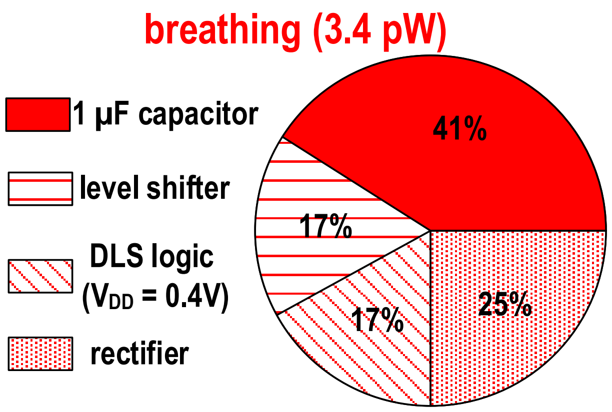
- ❑ TENG is operated at an input frequency of 3.2Hz [2].
- ❑ Total charge transferred between the electrodes of TENG is 52nC (Fig. 9).
- ❑ Keithley 6517B need to use for testing the TENG in order to avoid electrostatic discharge.
- ❑ Sample test set up for characterizing the TENG is shown.

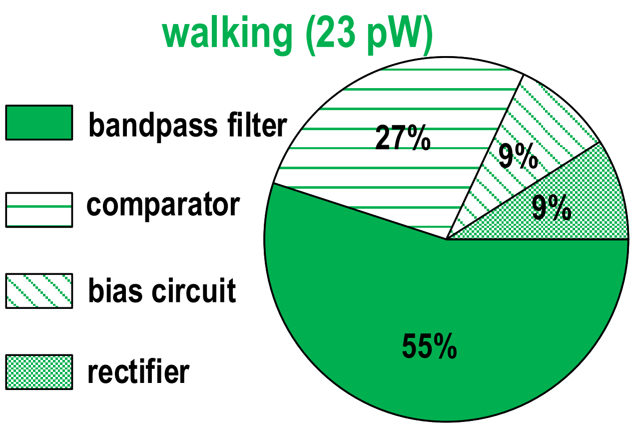
TENG Analysis

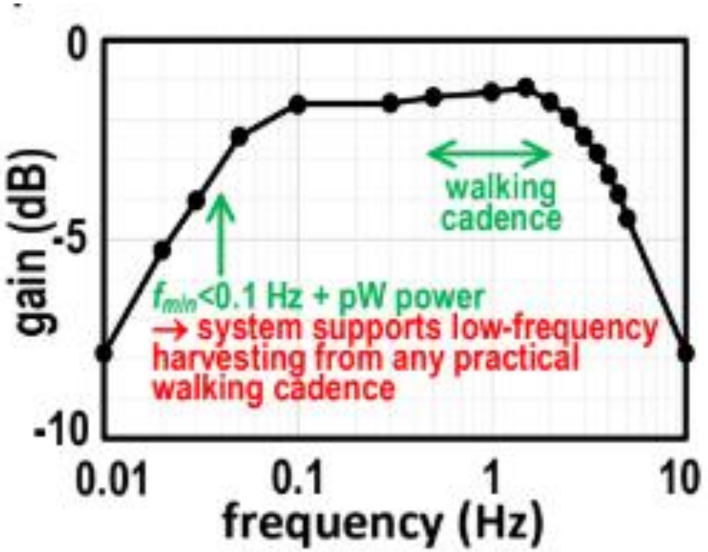




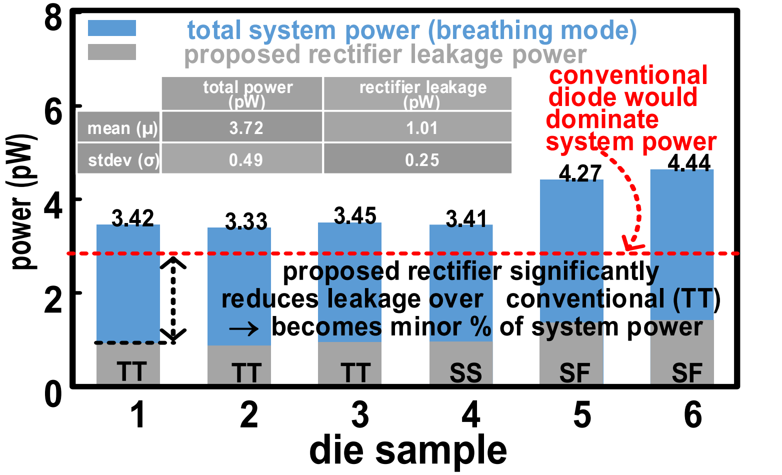
Testchip and System Measurements



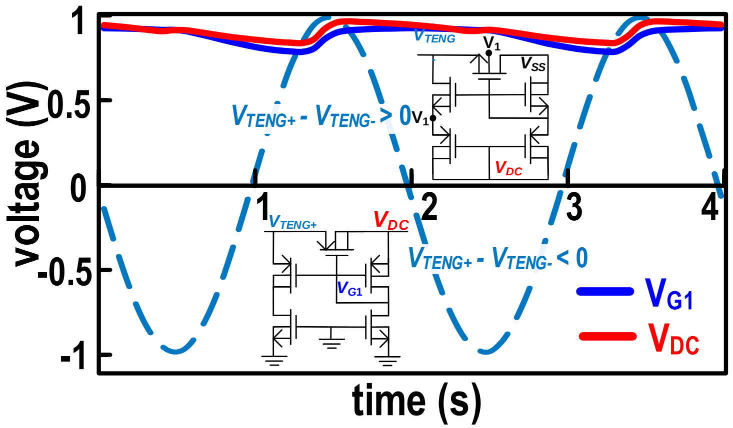




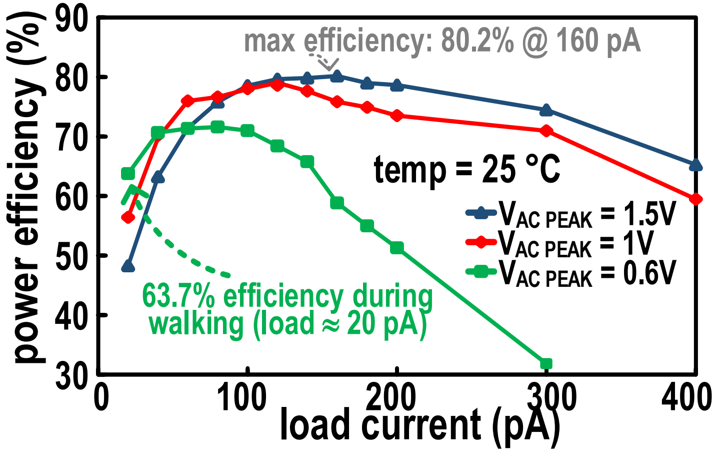
SYSTEM AND RECTIFIER POWER (BREATHING MODE)



ACTIVE RECTIFIER RESPONSE (Fig. 2)

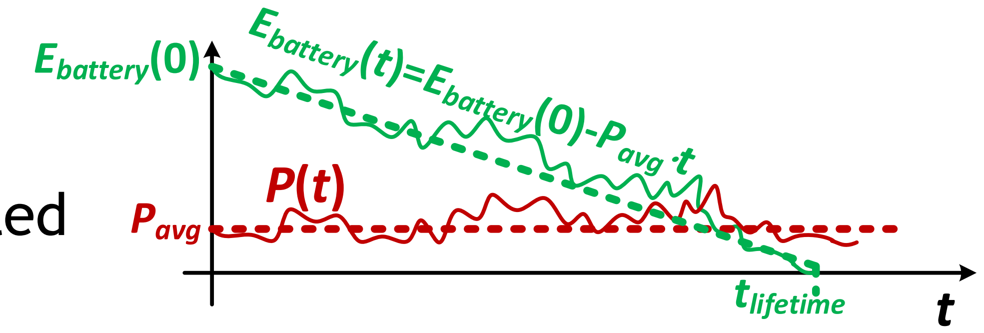


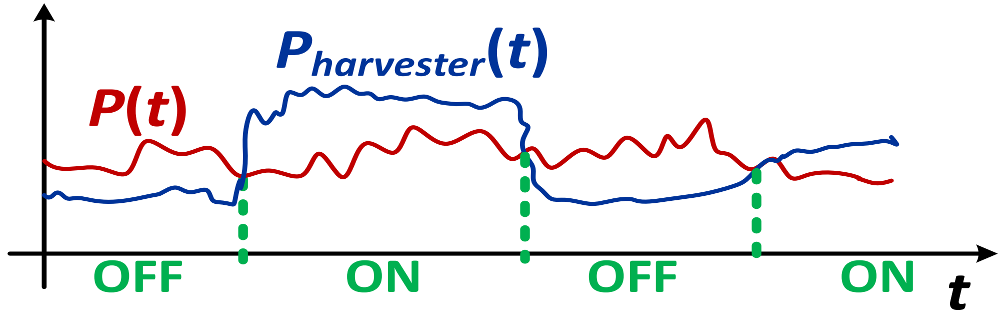
POWER EFFICIENCY VS. LOAD

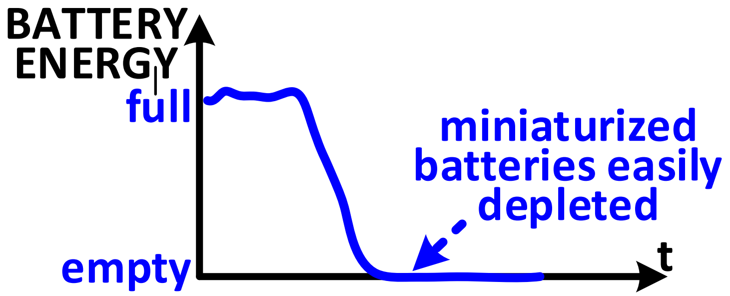


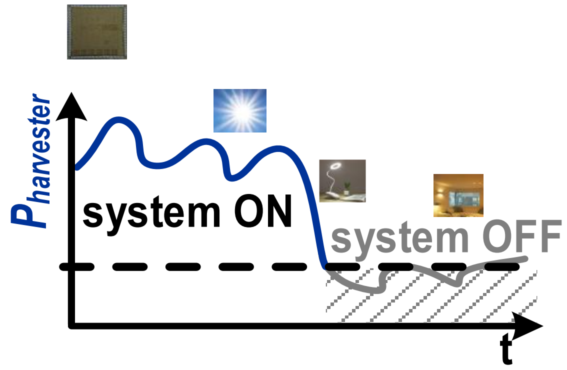
Power and System Design Implications

- Power target vs. energy source
  - w/battery : 
    - Average power limits function feasibly executed
    - Battery life
  - w/o battery : 
    - Harvested power
    - Peak power matters
  - Power profile :
    - Patterns of the power/power profile coupled affect the type of decision
    - Always-on
    - Duty cycles
    - Event-driven

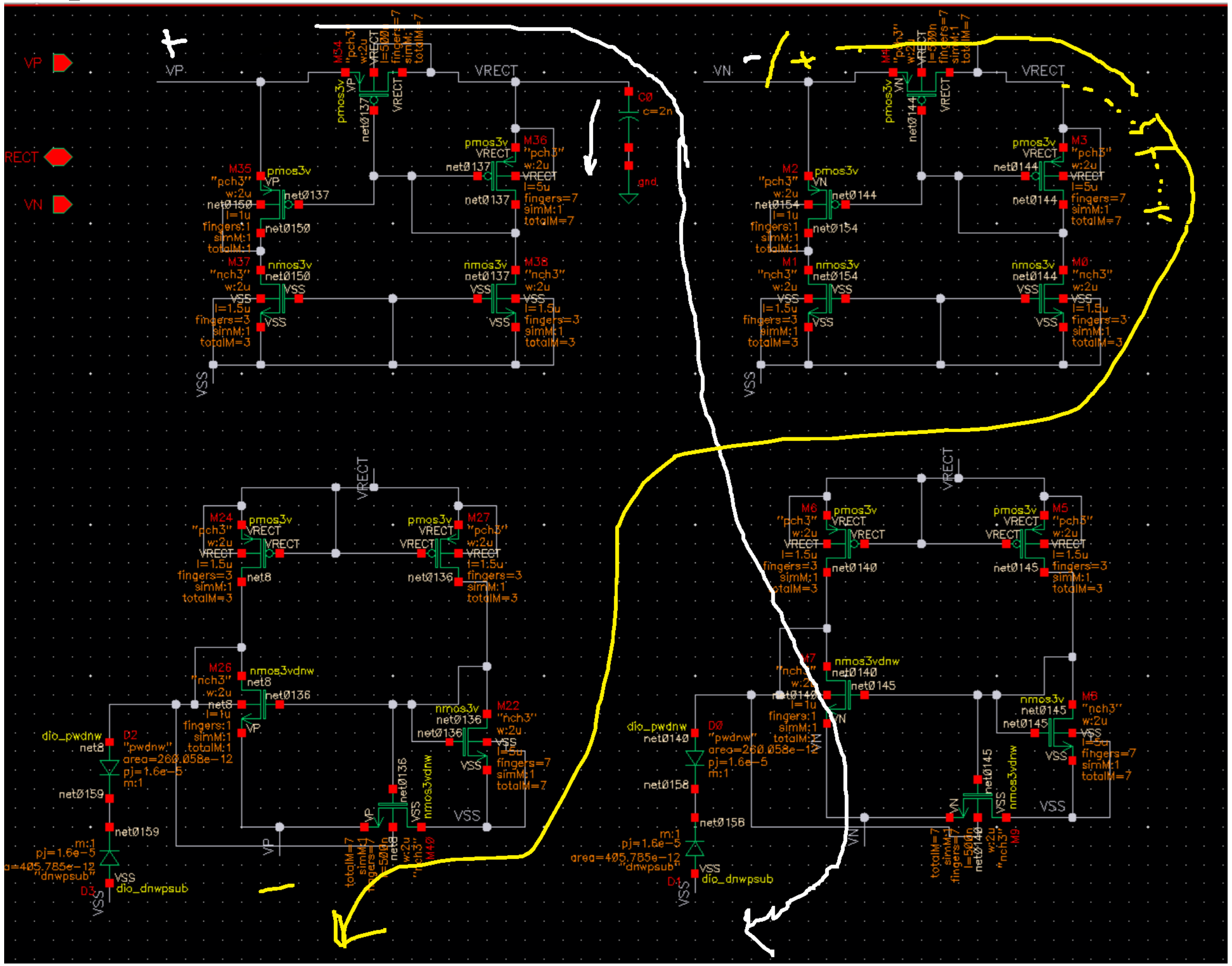






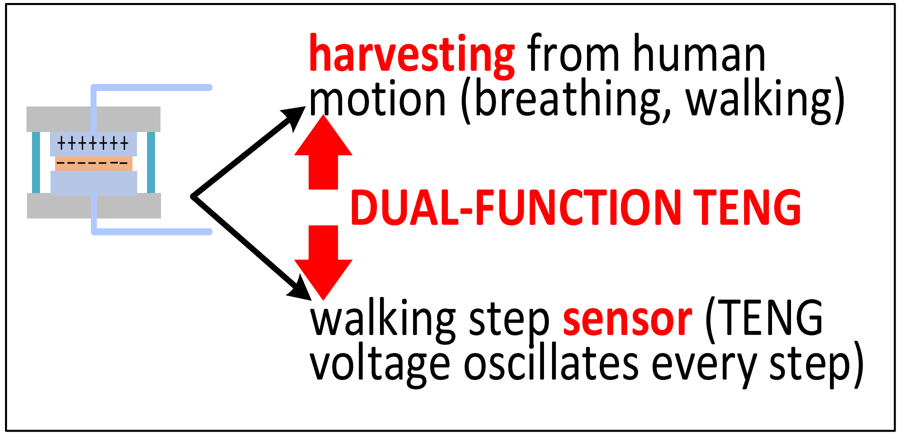


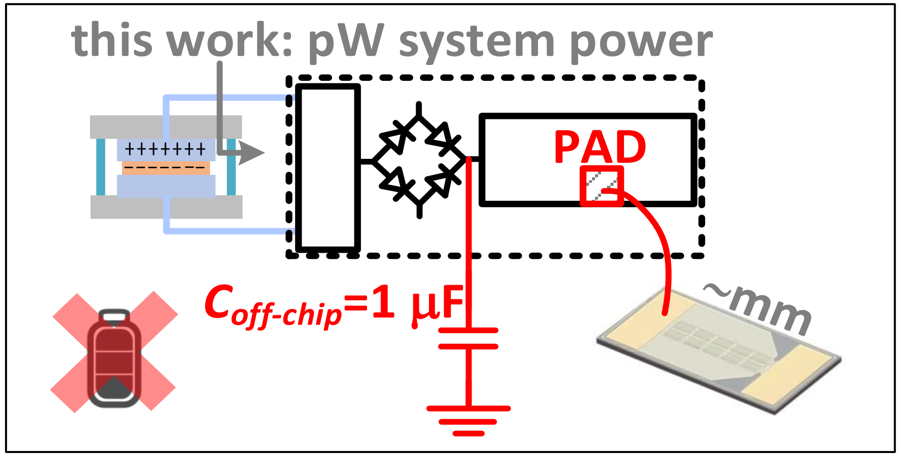
Operation of the ULP rectifier



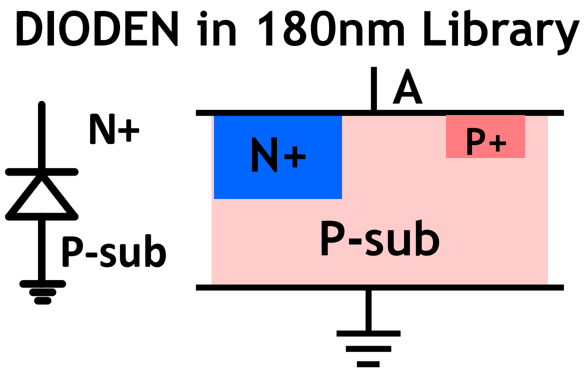
Energy Harvesting and Power Management

- TENG-CHIP co-design for low voltage operation
  - integrated over-voltage and rectifier into silicon chip and used std CMOS.
- Sensing the walking event
  - Dual-function TENG
- Regular harvesting from breathing
  - Time-bounded event repetitions -> store energy with very small cap
- Harvesting from walking
  - just-in-time harvesting power provision to support step sensing and counting

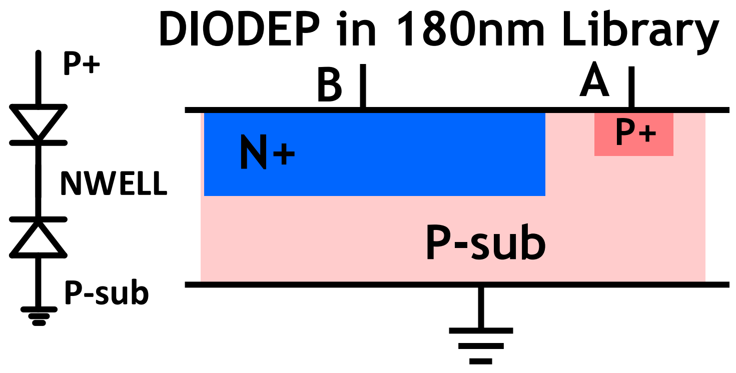




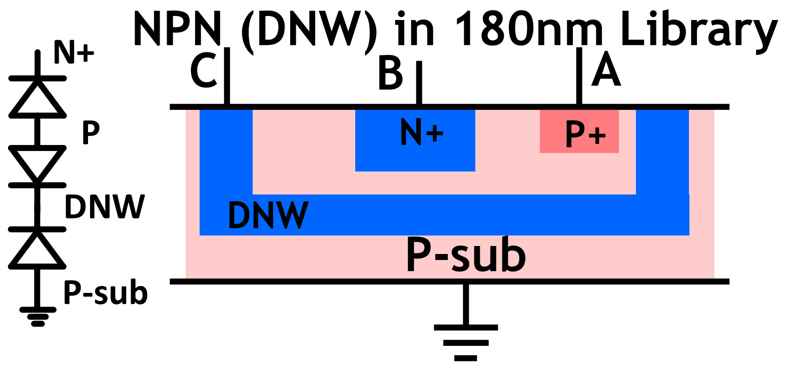
Over Protection Circuit - Analysis



CAN ONLY CLAMP +VE WAVE



CAN ONLY CLAMP +VE WAVE

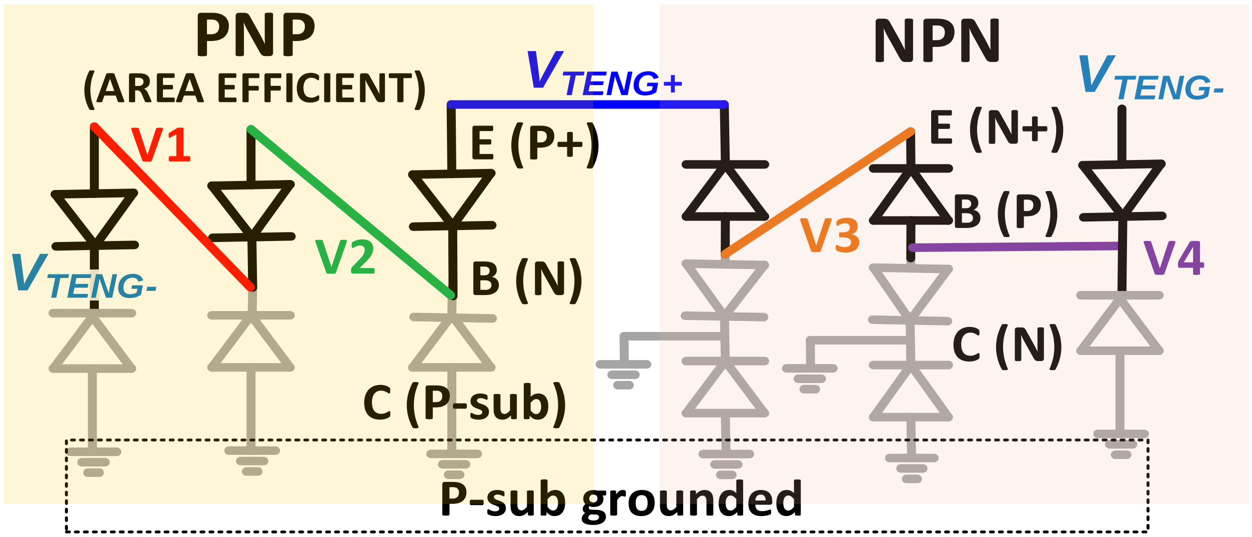


CAN CLAMP +VE AND -VE WAVE

PROPOSED OVER PROTECTION CIRCUIT

2-PNP & DIODEN

2-NPN & DIODEN



MEASURED RESPONSE