New Opportunities for In-Situ Space Weather Awareness via Nanosatellites Enabled By Advanced Manufacturing and Quantum Technologies

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Problem Statement

The explosive investment in quantum technology over the past decade is transforming the development of high-performance, low SWaP sensors. Meanwhile, advanced manufacturing technologies are driving significant progress in autonomy, artificial intelligence, and connectivity. By contrast, space-based systems value conservative engineering, reliable technology, and flight-proven hardware.

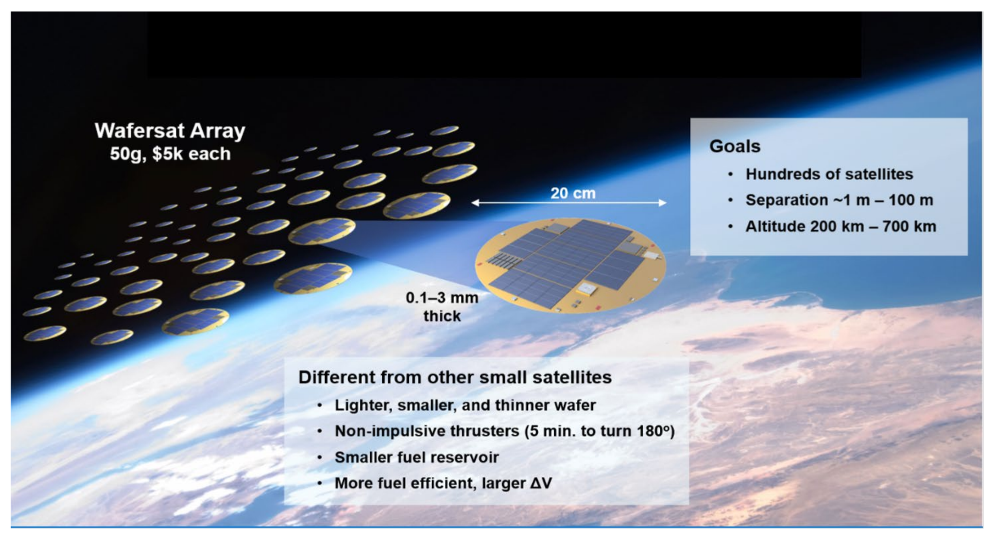

Figure 1: Silicon wafer scale satellite concept. X. A. Zapien, MEng Thesis, MIT 2020.

Cadets at the United States Military Academy are challenging this paradigm by envisioning what could be possible when integrating advanced microelectronics manufacturing and quantum technologies into nanosatellites for persistent space weather awareness.

I. Gallium Oxide

Far UV photodetectors could be used to measure LEO electron density, by inferring the electron concentration from photons emitted during the relaxation of metastable atomic oxygen produced by electron collisions. Gallium oxide detectors utilize β-Ga_2O_3 as the wide-bandgap semiconductor in solar-blind ultraviolet photodetectors to enable higher efficiency. Currently, GaN, SiC, and ZnO are the materials primarily used. However, β-Ga_2O_3 is a more effective option as its ultra-wide band gap of approximately 4.9 eV makes it more suitable for higher voltages. Additionally, the ultra-wide band gap gives the photodetector a shorter absorption cut off edge, exceptional stability, and a high resistance to radiation.

β-Ga_2O_3 is also a more cost-effective option as it has a comparatively small growth cost. If successful, devices developed with β-Ga_2O_3 will have higher power conversion efficiency and smaller conduction losses. Therefore, β-Ga_2O_3 will be especially useful in devices requiring a large amount of voltage and power. Although β-Ga_2O_3 is a promising semiconductor material for solar-blind ultraviolet photodetectors and the technology has been improving over time, further development of β-Ga_2O_3 detection is needed as issues with low conductivity, large dislocation densities, and crackling of the deposited film have arisen in testing.

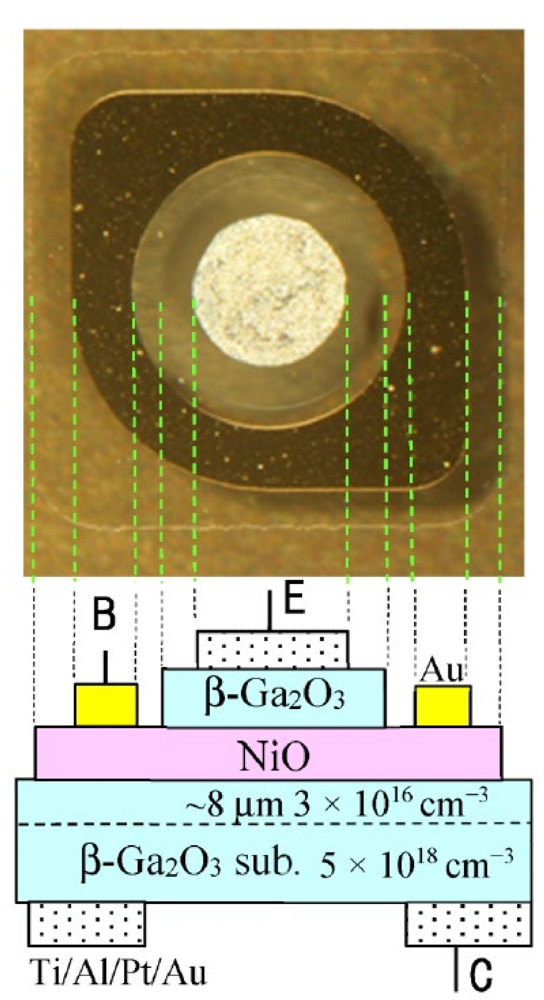

Figure 2: UV detector with Ga_2O_3 – NiO heterojunction. S. Nakagomi, Sensors, 2023.

II. Diamond Magnetometers

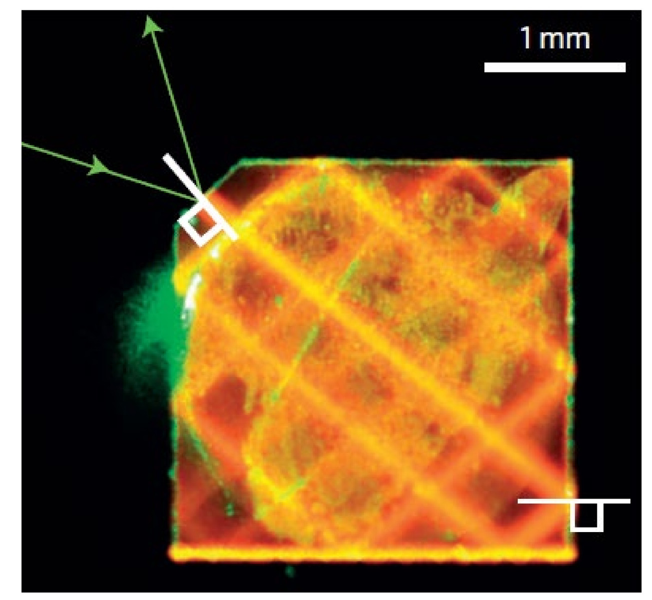

Figure 3: Nitrogen vacancy diamond waveguide magnetometer. H. Clevenson et al, "Broadband magnetometry and temperature sensing with a light-trapping diamond waveguide" 2015.

Interaction between the Earth's magnetic field and the solar wind is the fundamental driver of space weather effects. Accurate measurements of the magnetic field are crucial for both scientific studies of the ionosphere and operational decision-making. New solid-state magnetometer technology based on nitrogen vacancy (NV) centers in diamond promises sensitivity close to that of superconducting detectors, but with dramatically lower size, weight, and power.

These detectors take advantage of the Zeeman Effect, which breaks the degeneracy of atomic spin states in the presence of a magnetic field. A green laser is used to populate a given energy level, and a microwave photon then populates the upper energy state of a split line. Decay of that state produces a red photon which is the readout signal. Because the upper level energy is a function of magnetic field strength, by scanning the microwave energy while monitoring the readout intensity the magnetic field can be determined.

III. FDSOI Subthreshold Microelectronics

For a small satellite, the power consumed by the electronics is a significant issue. Small satellites may have only tens of watts of power generation capability, which is ~10x less than that consumed by typical CPU's. Thus on-board data processing is limited, which in turn puts the burden on data transmission which is also very costly. Subthreshold microelectronics is an emerging technology ideally suited to the space environment. By reducing the operating voltage by a factor of 3, the energy required for computing is reduced by 9x.

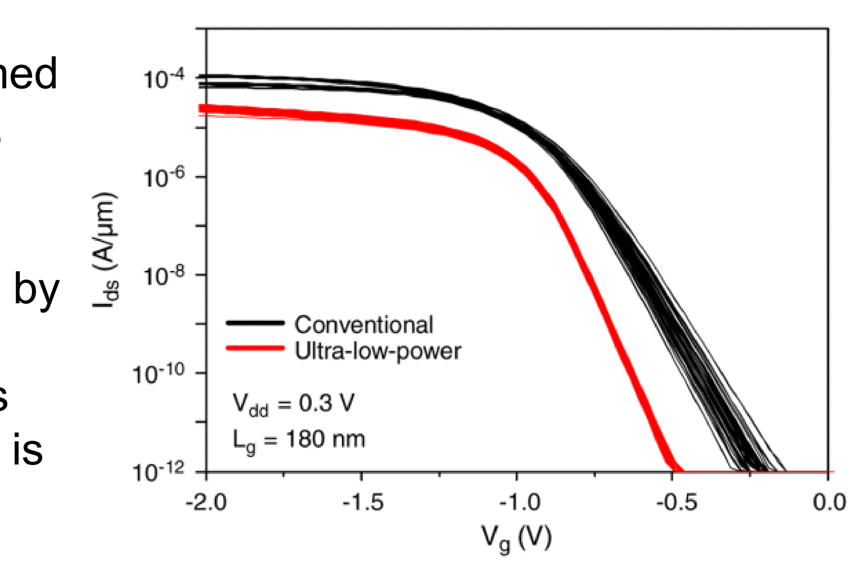

Figure 4: Extremely energy efficient transistor I-V characteristics. S.A. Vitale, etal., "Work-Function-Tuned TiN Metal Gate FDSOI Transistors for Subthreshold Operation" 2010.

Historically, subthreshold microelectronics have been limited by variability as the transistor drive current is exponentially sensitive to variations in threshold voltage (V_T). Recent work has demonstrated that mid-gap metal gate transistors fabricated on a fully-depleted silicon-on-insulator platform (FDSOI) exhibit 10x lower V_T variation. A world-record low power microcontroller as well as other technologies have recently been demonstrated in subthreshold circuits. In addition, FDSOI is an inherently radiation-hard process technology, as the thin silicon channel cross section greatly reduces the sensitive volume and thus the rate of single even upsets (SEUs).

IV. Microelectrospray Propulsion

Electrospray micropropulsion aims to accelerate small spacecraft, such as a Cubesat, in an efficient, cost-effective manner that provides a large amount of versatility and control. Propulsion on CubeSats has been very limited in the past, but systems such as vacuum arc thrusters, cold gas propulsion thrusters, and electrospray thrusters have been used. The two primary issues with CubeSat propulsion today are size and power consumption. Other important considerations are cost, commercial availability, and dependability. Electrospray micropropulsion generates thrust through the ejection of charged particles created from an electric field. It is beneficial as it is not constrained by an energy rate from a chemical reaction and performs better with miniaturization. Furthermore, the device can potentially be fabricated through 3D printing, which would significantly decrease costs and increase commercial availability.

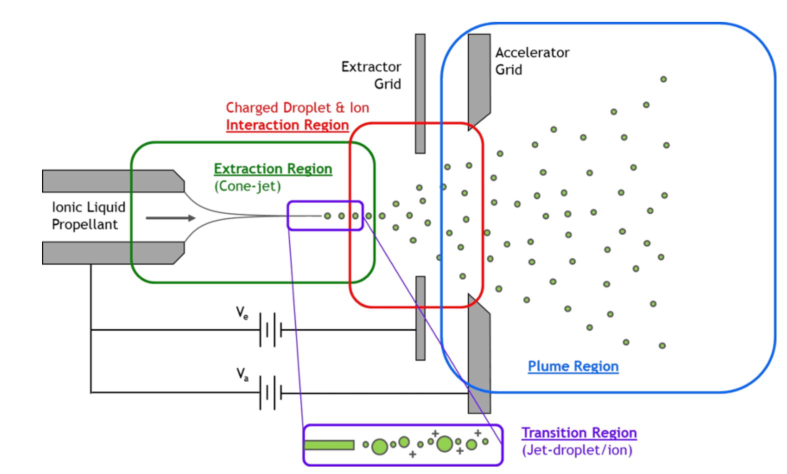

Figure 5: Schematic of electrospray thruster. H. Huh, et al, "Numerical Simulation of Electrospray Thruster Extraction", 2019.

If successful, electrospray micropropulsion would allow for the direct propulsion of CubeSats and other small satellites that would enable them to perform longer, more advanced operations at a lower cost. A proof-of-concept demonstration has been conducted by the MIT Department of Mechanical Engineering on the potential for 3D printing a scalable electrospray micropropulsion thruster, but more development is needed on improving aspects of the design to make it more efficient.

V. Advanced Packaging

As Moore's law scaling becomes increasingly difficult, semiconductor manufactures are turning to novel packaging technique to increase computational density. It is now possible to interconnect dozens of chips.

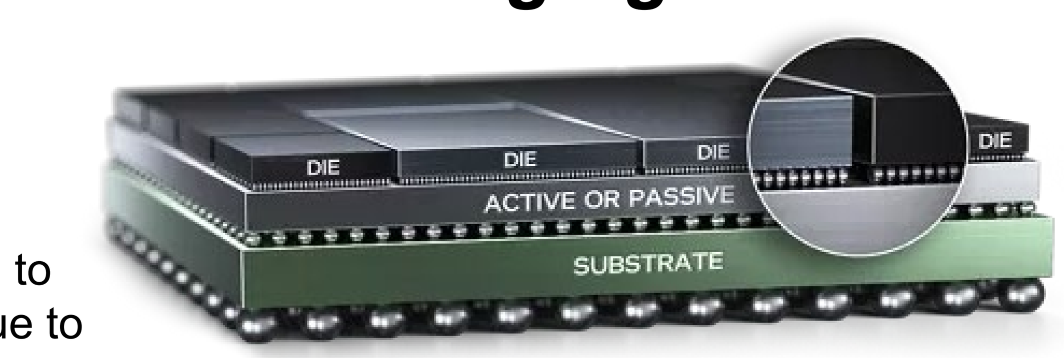

Figure 6: 3D integration with Intel Foveros and EMIB packaging. https://www.intel.com/content/www/us/en/foundry/packaging.html

Heterogeneous integration simultaneously reduces the energy cost and increases the bandwidth of data movement. Plus, it saves significant weight and volume which is particularly important for small satellites. Advanced packaging promises to enable AI and autonomy in the smallest satellite platforms. It is an important next step to study the reliability of heterogeneous integration in the space environment.

Acknowledgements

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