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A Review on Micronchannel and Minichannel Cooling Techniques for High-Density Electronic Devices

Jenitha Pilli[1], Prathik Kumar Jannu[2], Javed Ali Mohammad[3], Sri Harsha Panchali[4], Usha Mohani kavirayani[5], Krishna Bhardwaj Mylavarapu[6],
[1]MS in Computer Science, University of Louisiana at Lafayette.
[2]Computer Science Engineering, JNTU Hyderabad.
[3]Masters in Data Science, New England College.
[4]Information Systems Engineer, CrowdStrike Inc.
[5]Kent State University, MS in Computer Science.
[6]MS in Computer Science, University of Illinois Springfield.

Abstract: Electronic systems for diverse applications have undergone multiple phases of development over the past fifty years. The downsizing of power converters has grown more dependent on a number of parameters, including their high-power density, efficiency, cost, and operating temperature. The present academic review presents a thorough assessment of the microfabrication techniques, advancing the properties of materials, and the cooling ways applied for the smallest and most high-tech electronic devices. Among the recent advances in flexible sensor substrates, the LIGA process, etching, laser micromachining, additive manufacturing, and the coming 3-D surface-enhancement technologies, all have a strong impact on the development of electronic systems that are smaller but still powerful. These advancements go hand in hand with the microchannel cooling methods of single-phase and improved microchannel heat sink that are both analyzed for their capability to manage the growing thermal needs of the compact, high-power devices. The load flow distribution techniques such as both AC and DC load flow methods are also brought up to emphasize their role in assuring reliable electrical performance in complicated power systems. In addition, the main applications of high-density electronics, such as data center optical circuit switching, smart-grid power electronics, LED lighting, and laser-diode operation, are examined in order to demonstrate the real-world impact of the technologies. The study, thus, highlights the significant interaction between microfabrication, thermal management, and system-level applications as one of the major factors that propel the development of next-generation high-density electronic devices.

Keywords: High-Density Electronics, Power Converter Miniaturization, Microfabrication, Electronic System Integration, Microchannel.

1. Introduction

The complex processes involved in making working electronic devices include fabricating an interconnect layer to connect the chip's components and then putting the chip onto it. The integration of electrical components with a conductive connection layer over a flexible substrate is a fascinating new topic for next-generation electronics called flexible electronics. This technology has the potential to create devices that are foldable, lightweight, rugged, portable, and bendable [1]. In order to take advantage of these flexible devices' many uses, researchers have been working on new manufacturing methods, materials, and structural design strategies for flexible devices. These devices have the potential to supplant more traditional, rigid devices in industries including biotechnology, communication systems, and display.

Air conditioning split systems, absorption cycles, and electric chillers are some of the individual methods that can be employed to fulfil cooling demand [2]. Another option is to apply a single solution to all of the buildings in the cluster. Also, cooling methods like air-forced convection and liquid active cooling need a lot of energy, which is an issue. Research into ways to maximize energy utilization without sacrificing thermal regulation capabilities is necessary since striking a balance between accurate temperature control and energy efficiency is no easy feat. Equally important is the development of cooling methods that can endure extremes in both operational temperature and other environmental factors. Another problem with active cooling methods is how much energy they use. This includes air-forced convection and liquid active cooling. Research into ways to maximize energy utilization without sacrificing thermal regulation capabilities is necessary since striking a balance between accurate temperature control and energy efficiency is no easy feat. In addition, it is of the utmost importance to develop cooling solutions that can endure extreme operating conditions and temperature changes.

Technological advancements in the computer, automation, and electro-communications sectors have restructured knowledge in these areas, which in turn have far-reaching effects on many facets of human existence [3]. When dealing with high temperatures in small spaces, modern power electronics, consumer electronics, and miniature mechanical and energy systems have challenges in improving the cooling effect [4]. As a result, microchannel and mini-channel cooling with single or two-phase flows is one of the suggested methods due to its excellent heat transfer performance. The versatility of mini- and microchannels made them ideal for use in numerous cooling applications. Biomedical engineering (functional product dosage, injections, and chemical analyses).

1.1. Structure Of The Paper

The paper is organized in this manner: Section II discusses important techniques in microfabrication and materials. In Section III, the focus is on single-phase microchannel cooling together with the various methods of enhancement. AC load Flow and DC load flow are described in section IV, Section V introduces the theme of the high-density electronics application. A summary of the present literature is given in Section VI, while Section VII concludes the discourse with perspectives and future directions.

2. Microfabrication And Material Techniques

Manufacturing technology advancements are making the realization of interaction circuits with microstructures a reality. When compared to conventional machining techniques, the capacity to fabricate tiny circuit architectures opens up novel possibilities for vacuum electrical devices that generate radiation at terahertz (THz) frequencies. The band of electromagnetic waves known as terahertz (THz) lies between the infrared and microwave regions of the spectrum. Applications in the military and space travel, where weight and size are paramount, benefit greatly from the reduced size and weight of components made possible by the shorter wavelengths at THz frequencies.

2.1. Substrate Materials In Various Types Of Flexible Sensors

Sensor devices have definitely made lives better. The abundance of sensors in modern smartphones allows them to track a wide range of physiological data, including location, health, exercise data (such as step count), heart rate, and more [5]. The use of flexible sensors in gadgets enables the development of multi-functional devices, which in turn overcome the limitations of conventional wristwatches.

- Crystal Silicon: The most common substrate for sensor development up to the last ten years has been single-crystal silicon because of its many benefits, such as cheap cost, minimal power losses, and high sensitivity. Despite their extensive use, these inflexible silicon sensors have a number of drawbacks, including brittleness, high production cost, high operation power, and fragility [6]. Notwithstanding these limitations, flexible sensors have recently attracted a lot of interest from academics and businesses.
- Humidity Sensors: A piezoelectric ZnO thin film was deposited onto a graphene oxide (GO) sensing layer, which was incorporated into flexible humidity sensors that were constructed using a polyimide substrate [7]. To create GO thin films, 4 µL of GO at different concentrations was dropped onto the devices' surfaces and allowed to evaporate. These bendable sensors proved their reliability and versatility for industrial uses by remaining functional even after being bent eight thousand times. The results from the respiratory sensors are displayed in Figure 1.

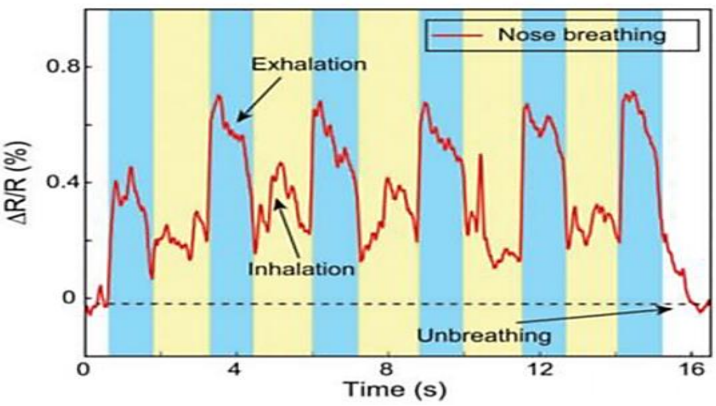

Figure 1: Output From the Flexible Respiratory Sensor Showing Distinct Peaks for Inhalation And Exhalation

- Pressure Sensors: Pressure sensors have recently been a popular subject in the realm of flexible sensors due to their versatility. The forces acting on a given surface can be detected using these sensors. Medical diagnostics and touch screen gadgets are only two of the many uses for pressure sensors [8]. Capacitive and resistive pressure sensors, which transform mechanical stress into electrical data, are the most practical and economical options.
- Temperature Sensors: A number of sectors rely on temperature readings, including those dealing with food storage, climate management, and aviation. When measuring temperature, even small changes can have a big impact; thus, the sensor's sensitivity, response time, accuracy, and dependability must be top-notch [9]. Temperature data can reveal the vital state of a factory, the steadiness of an automobile's engine, or even an individual's health. Using a large-scale flat-bed knitting machine, a metal-based sensing layer was put into the knitted layers to construct the sensor (Figure 2).

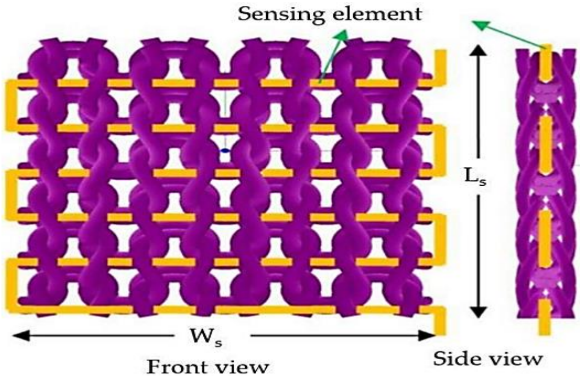

Figure 2: A Textile Temperature Sensor, Metal Rods Are Intertwined With The Fabric

2.2. Fabrication Methods

Traditional rigid electronic fabrication technologies can't meet these needs, so researchers need to look into new flexible fabrication technologies that can help make it easier to design and make electronic products that are flexible and stretchable, especially for wearable tech. Wearable electronics have come a long way in terms of design freedom, weight, integration, and multifunctionality thanks to the persistent advancement of novel fabrication techniques.

- LIGA: German for "lithographic," "galvonoformung," and "affirming," LIGA stands for the three processes of lithography, electroforming, and melding. Created in the early 1980s, LIGA technology is a micro manufacturing approach that enables the on-demand production of high aspect ratio structures with a lateral accuracy of less than one millimetre [10]. Here is a typical LIGA procedure, as seen in Figure 3.

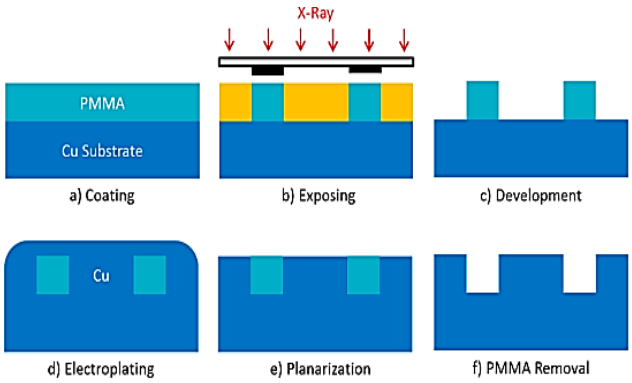

Figure 3: Process Flow Diagram Of Liga

- Etching: An integral part of micro fabrication is the etching process. A manufacturing technique known as etching involves removing layers from a wafer's surface. A lot of etching happens to every single wafer because this is such a vital procedure [11]. Masking material is utilized in numerous etching processes to prevent etching by shielding the wafer from the etchants.
- Laser Micromachining: A micromachining laser can have a pulse duration ranging from femtoseconds to microseconds, a repetition rate ranging from single pulses to Megahertz, and a wavelength matching the desired application. These features enable high-resolution micromachining in both the depth and lateral dimensions. To generate extremely thin surface patterns extending in the micrometre domain, micro-machining encompasses a wide range of production techniques, including drilling, cutting, welding, ablation, and material surface texturing.
- Additive Manufacturing: Additive manufacturing (AM), also known as 3D printing, has revolutionized the creation of several goods, from simple prototypes to complex buildings. This methodology goes against the grain of conventional subtractive manufacturing by building products from 3D model data by layering materials. Accuracy, quality, and utility are all aspects of AM that are enhanced by the various important processes that make up the overall pipeline.

2.3. 3-D Technologies for Surface Enhancements

Polymers are being used more and more, especially in places where prices are being pushed up, like the market for disposables. While polymers are more cost-effective in the long run, they are only practical in bulk and cannot compare to the mechanical and thermal resilience of materials like glass and silicon. Direct fabrication, which typically makes use of radiation to shape the polymers, and replication procedures involving molds are the two main categories into which polymer manufacturing falls.

- High Aspect Ratio Micromachining (HARM): Micromachining is the first tooling stage in HARMs, which also includes injection melding, embossing, and, if necessary, electroforming to create metal parts with replicated microstructures. Among the most alluring technologies for microstructure replication, it offers an excellent performance-to-cost ratio.
- 3-D Lithography: An effective way to create intricate structures with minute details could be discovered using a three-dimensional micro manufacturing technique that uses a certain type of light-activated molecules to selectively initiate chemical reactions in different materials, such polymers, .This new technique, known as "two-photon 3-D lithography," might revolutionize many different industries, including those dealing with microfluidics, optical storage, photonic switches and couplers, sensors, actuators, micromachines, and even scaffolds for constructing living tissue. But it's not yet a widely used tool.
- Electric Discharge Machining (EDM): EDM is a revolutionary method that can produce components from nearly any conductive material by employing machine shop manufacturing techniques. Despite its numerous uses in MEMS prototype fabrication, the spark erosion approach is too sluggish for batch processing.

3. Single-Phase Microchannel Cooling

The necessary removal of the high heat flux from the technological gadgets is still an enormous challenge, even if electronic cooling systems have come a long way in the past few years.

3.1. Microchannel Cooling

The electrical industry makes extensive use of a variety of cooling techniques. A lot of research has focused on single-phase flows in microchannels. Here are the current cooling modes, broken down by their heat transfer effectiveness:

- Forced Convection Air Cooling: The order of effectiveness for removing heat flux from a liquid is as follows forced convections of liquids, liquid evaporation, and air. Forced air convection is commonly used to cool computer circuits, including the central processing unit (CPU), even though it isn't as effective as radiation or natural convection at removing heat. The function of cooling fluids in total cooling performance is well-known to be significant, second only to heat removal mode.
- Forced Convection Liquid Cooling: A microchannel heat sink that uses forced convective liquid cooling is one of the most effective and promising cooling systems for tiny electronic devices that produce a lot of heat. Not only can this new cooling method drastically reduce package size, it can also be integrated onto chips.
- Microscale Cooling System: The electrical equipment and appliances that produce a lot of heat can be adequately cooled using microscale cooling systems. Micro heat pipes and heat sinks based on microchannels, for instance, substantially outperform conventional heat exchangers in terms of heat transfer efficiency. Researches and businesses alike have taken an interest in microchannel-based cooling systems due to its small size, low weight, adaptability to tiny electronic devices, and efficient cooling capabilities.

3.2. Methods used to Enhance the Thermal Efficiency in Microchannel Heat Sinks (MCHSs)

D.B. Tuckerman and R.F.W. Pease came up with the idea for the MCHS at Stanford University in 1981. For electronic device heat transmission, the MCHS is a heat sink with micro extrusions that lets the working fluid flow through it. Due to its small route size and great area to volume ratio, microchannel heat sinks are able to create extremely high heat transfer rates. Heat sink topology refers to the configuration of heat sinks in a thermal management system, as seen in Figure 4.

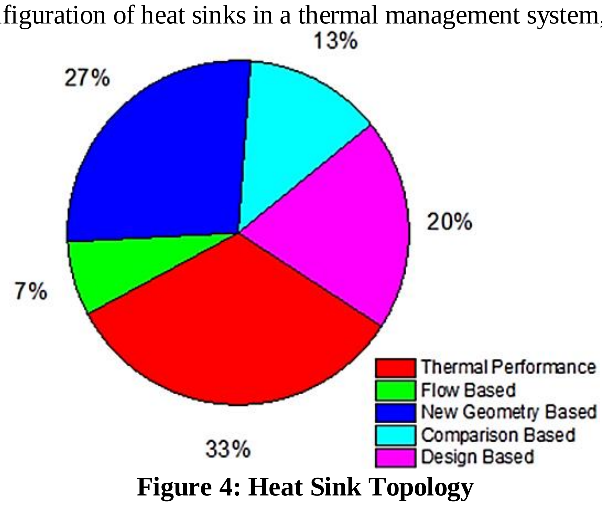

Figure 4: Heat Sink Topology

- Active Technique: Smooth rectangular MCHSs can have their thermal efficiency improved via active approaches that draw on external energy sources. Microchannel heat sinks can have their thermal performance improved using active methods, which include drawing electricity from an outside source.

- Flow Disruption Technique: A strategy to enhance thermal transfer within Microchannel Heat Sinks (MCHSs) involves the implementation of fluid flow obstruction. This method is based on the idea of creating turbulence in a flow channel by adding tiny objects into it. To enhance heat dissipation, one must lower the thermal boundary layer thickness and increase the convective heat transfer rate. The flow impediments that MCHSs can employ range from micro fins and pin fins to micro dimples, micro holes, micro ridges, and so on. The purpose of these microstructures is to promote heat transmission through the formation of swirls and vortices.
- Ribs: The installation of ribs is a typical technique for MCHS wall flow disruption [12]. Ribs are small projections that can be arranged in a number of ways on the channel's side walls. Two common patterns are staggered and parallel. These ribs lower the temperature of the thermal boundary layer and raise the heat transfer coefficient by creating flow turbulences.

3.3. Load Flow Distribution Electrical Power Systems

Load flow is the process by which the fundamental frequency steady-state voltages of electricity grids are calculated. In power system jargon, "load flow" refers to the network's steady-state solution. Modeling the power system, the electric network determines the voltage and steady-state powers at various buses. In terms of load flow, two main categories exist:

3.3.1. AC Load Flow Methods

AC load flows are usually what are used for standard load flow methods. An examination of the distribution and transmission of alternating current (AC) is fundamentally a study of AC power flow at grid-wide steady-state. By analyzing the electric loads and generation at different buses in the system, the steady-state values of bus voltages and line power flows can be calculated using the AC power flow method. In order to resolve the simultaneous nonlinear power flow equations of even the most fundamental power systems, iterative approaches are required. A number of techniques exist for resolving nonlinear equations; some examples include the Fast Decoupled, Newton Raphson, and Gauss Seidel methods.

- Newton Raphson: Wasley and Shlash proposed the three-phase Newton Raphson power-flow due to strong convergence. According to Arrillaga and Arnold, the rapid decoupled three-phase Newton-Raphson.
- Gauss Seidel: The Gauss-Seidel method can be used to solve a system of linear equations. Philipp Ludwig von Seidel and Carl Friedrich Gauss, two German mathematicians, were the namesakes of the approach. In iterative approaches, the Gauss-Seidel method can be used to solve systems of non-linear algebraic equations.
- Fast Decoupling: The efficiency is achieved by modeling the effect of branch outages using sparse matrix methods, an iteration strategy that has been empirically established, the decoupling of the actual and reactive power equations, and the matrix inversion lemma.

3.3.2. DC Load Flow Methods

DC Load flow is a useful tool for analyzing potential outcomes. More and more, power systems are utilizing it for techno-economic analysis and real-time dispatch because of its simplicity and resilience. When it comes to electricity markets and contingency analysis, as well as techno-economic research generally, DC power flow is a valuable instrument [13]. Prior studies have shown that the two most critical power system indicators for a precise DC power flow solution are a flat voltage profile and a high X/R ratio.

4. Applications in High-Density Electronics

Power electronic systems for diverse applications have undergone multiple phases of development over the past fifty years. Starting in the late 1980s, its progress, particularly in terms of high power density, has been immensely expedited. In the quest for ever-smaller power converters, efficiency, affordability, and operating temperature have emerged as critical success factors alongside high-power density. Goes into the numerous uses of electronics in different industries later on:

4.1. Optical Circuit Switching in Cloud Data Centers

The advantages and possibilities of optical components have led to a recent uptick in interest in optical networks for data centers [14]. The suggested design for the data center's network makes use of OCS. Short circuits are formed by aggregating packet flow. The controller is asked to assign the resources required to construct the circuit by means of a control packet, in accordance with a two-way reservation method similar to that proposed for optical burst switching networks [15]. It is not feasible to implement such a two-way reservation in long-haul backbone networks, as mentioned earlier, but it is suitable for data centers [16]. The controller can then manage the resources by sending a control packet back to the sending node. Afterwards, the controller establishes a previously determined route for the data packets to follow within the circuit.

4.2. Power Electronics for Smart Grid

Modern grid codes establish voltage and frequency curves that correlate perturbations in those variables with a designated clearance time. The goal of grid codes is to ensure service and avoid system blackouts; if the disruption continues for more than the stipulated duration, a safety disconnection is requested. However, there are situations where the exact opposite is requested; specifically, a disconnect prior to the maximum clearing time, so that the system can be stabilized before the disconnect.

4.3. Generation of White Lightening LED

Longevity, small size, portability, efficiency, lack of toxicity (no mercury), and very little infrared and ultraviolet light are just a few of the ways in which LED technology easily outshines more traditional light sources. Additionally, light-emitting diode lighting presents itself for predetermined spectral contents, aesthetics, and biochemical and biophysical impacts [17]. For LEDs to provide white light that is as good as natural light, the color rendering needs to be perfect. Light that isn't the same color as sunlight or light from a filament bulb won't look natural and could irritate the eyes.

4.4. Laser Diode Cooling

Industrial applications for high-power, diode-pumped, solid-state lasers in cutting, drilling, and welding are numerous due to their extended diode bar lifetime, high output power, and excellent laser beam quality [18]. Nowadays, diode-pumped lasers are more common than flash-lamp pumped systems since diode bars are more powerful and cheaper.

5. Literature Review

The latest studies concerning the cooling methods for high-density electronic devices point out the advantages of such methods in terms of better thermal management, longer life of the devices, and high performance. The evolving of these techniques has resulted in the suppression of thermal bottlenecks, thereby, permitting higher power densities and incrementing the efficiency of the whole system.

Tam et al. (2019) suggests a portable and flexible wireless multichannel sensor system for the capture of high-density surface electromyography (HD-sEMG) signals. In its current iteration, the proposed sensor system makes use of low-power, high-quality, off-the-shelf components such as the Intan Technologies RHD2132 digital electrophysiology interface chip to record 32 surface electromyography (sEMG) channels, each with a sampling rate of 1 kHz and a sample resolution of 16 bits. According to the manufacturer's specs, the RHD2132 has an input-referred noise of 2.4 µVrms, which changes by about 15% with amplifier bandwidth, and a total power consumption of 49.5 mW [19].

Raszmann et al. (2019) shows how four SiC MOSFETs connected in series behave while switching and how well they balance voltages. When it comes to high-power converters, topologies with two levels or more levels can both achieve larger blocking voltages. With their simpler control mechanisms, higher density, and less complicated circuitry, two-level switching topologies are more appealing than multilevel topologies. Each gate-driver employs active gate control to dynamically regulate device turn-off speeds, thereby balancing the voltage across series-connected MOSFETs [20].

Du, Liu and Zhu (2019) details a method for preparing nano glass-particles in batch mode for use in applications requiring high density through glass. The advantages of this preparation process over current methods that use glass as a conduit include the ability to make the electrodes and packaged structure out of the same material, and theoretically, a spacing of less than 1 am between the electrodes within the packing [21].

Liu et al. (2018) Various heat dissipation methods have been utilized in modern high-power, high-density packaging systems. These methods include air forced convection heat sinks, two-phase cold plates, and single-phase liquid-cooled cold plates, among many others. Thanks to developments in nanotechnology, Micro/Nanoelectromechanical Systems (MEMS/NEMS) now have access to materials with low heat resistance and high conductivity, as well as a sintering connection method. To investigate the heat transfer capability required by high-temperature electronic product demands, a nano silver/graphene composite paste was created against this backdrop [22].

Wei et al. (2018) An innovative RC-IGBT, or reverse-conducting insulated gate bipolar transistor, is introduced and simulated here; this form of transistor is both very fast and does not necessitate snapback. On the collector side, there is a CTG, and between the CTG and the collection electrode, there is a bias voltage (VRC). During the forward conduction condition, when the VRC is smaller than zero, a layer of high-density hole inversion is formed surrounding the CTG. In addition to increasing the dispersed resistance and functioning as a folding controlled hole injector, the CTG also improves the efficiency of hole injection. By utilizing a tiny cell pitch, the CTG RC-IGBT is able to produce a low on-state voltage drop (VON) and avoid snapback. A layer of electron buildup forms surrounding the CTG in the blocking condition when VRC > 0 [23].

Belmonte et al. (2017) prove that the presence of an inherent field that energetically promotes the SET operation has a significant impact on the durability of triple-layer a-VMCO devices due to the asymmetry of the electronic band structure. To optimize the endurance lifetime, the RESET pulse should be more than 500 times longer than the SET pulse, and over time, the HRS state naturally transition to the LRS state. They demonstrate that endurance characteristics can be significantly enhanced by integrating the time-dependent HRS drift with the cumulative RESET effect while cycling [24].

Yang et al. (2016) This photonic TSV interposer is composed of germanium photodetectors (PD), optical (Mach-Zehnder Interferometer) modulators, tenable arrays waveguide grating (AWG), and monolithically integrated TSV. This 3D photonics architecture is made public along with its manufacturing technique. This on-package TSV integration module has a tenable 800

GHz channel, a silicon modulator with a 20 GHz bandwidth, and a germanium PD with a 28 GHz bandwidth. The 3D photonics module allows for a data throughput of 30 Gbps. Using a TSV interposer, this research paved the way for dense on-board optics modules in 3D silicon photonics packaging [25].

Table I presents a review of research on high-density electronic devices, organized by study, study focus, key contributions and findings, and relevance to high-density electronics.

Table 1: Summary Of Literature Review Based On High-Density Electronic Devices

Author(s) & Year	Focus of Study	Key Contribution / Findings	Relevance to High-Density Electronics
Tam et al. (2019)	Portable wireless multichannel HD-sEMG sensor system	Developed a 32-channel sEMG acquisition system using low-power components (1 kHz sampling, 16-bit resolution, 2.4 µVrms noise, 49.5 mW consumption).	Demonstrates compact, low-power sensing systems relevant to high-density electronic integration.
Raszmann et al. (2019)	Series-connected SiC MOSFET switching and voltage balancing	Shows improved voltage balancing using active gate control for two-level and multilevel converters.	Supports reliable high-voltage, high-power density converter designs.
Du, Liu & Zhu (2019)	Nano glass-particle preparation for through-glass-via (TGV)	Introduces a batch-mode process enabling <1 µm gap and identical electrode/packaging materials.	Enables finer packaging structures essential for high-density interconnects.
Liu et al. (2018)	Heat dissipation for high-power, high-density devices	Explores nano-silver/graphene composite materials for improved thermal transport in MEMS/NEMS.	Enhances thermal performance in dense electronic packaging.
Wei et al. (2018)	Controllable trench-gate RC-IGBT device	Offers a CTG-structured RC-IGBT that is snapback-free, has little voltage drop, and has better hole injection.	Provides higher efficiency and power density in power semiconductor devices.
Belmonte et al. (2017)	Reliability of triple-layer a-VMCO devices	Shows endurance improvement by exploiting HRS drift and RESET accumulation; RESET pulse needs >500× longer than SET.	Enhances reliability of high-density resistive memory devices.
Yang et al. (2016)	3D photonic TSV interposer	Integrates TSVs with AWG, MZI modulators, and Ge photodetectors achieving up to 30 Gbps data rate.	Demonstrates advanced 3D packaging for high-density optical interconnects.

6. Conclusion and Future Work

The high-density electronic devices which are in demand nowadays are characterized by small sizes and high-power consumption. The consequence of this scenario is that there is a demand for more sophisticated production techniques and heat control systems to ensure the proper functioning and high efficiency of the devices. The key microfabrication methods, materials of flexible substrates and new 3-D enhancement technologies that are used for miniaturized and high-performance components were reviewed in this research. Moreover, single-phase microchannel cooling techniques as well as their enhancement methods were evaluated for their contribution to combatting the high temperature produced by the compact systems. At technical discussion about load flow techniques, both AC and DC, the importance of an accurate electrical model was underscored if power stability to be obtained for the system. As a matter of fact, the different applications discussed like optical circuit switching, smart-grid electronics, LED systems and laser-diode cooling show the vast impact that these breakthroughs have on the field of modern electronics. The researchers have come to the conclusion that continual creativity in the fabrication, cooling and system-level integration will remain to be the mainstay of next generation high-density electronic devices.

Future studies are to intentionally carry on with the work of crafting microchannel cooling designs that will be more efficient, integrating advanced materials that will possess superior thermal properties, and optimizing methods of fabrication for small-sized structures. In addition to this, next-generation high-density electronic devices will be further supported by better modelling accuracy, hybrid cooling systems, and reliability under extreme operating conditions.

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