Scientific Journal for Publishing in Health Research and Technology

Volume 2, Issue 2, 2026, Pages: 46-57

Journal homepage: https://sjphrt.com.ly/index.php/sjphrt/en/index

Optical Performance Study and Metallic Absorption in Nanostructured Plasmonic Systems for Solar Unit Cell Design

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دراسة الأداء البصري والامتصاص المعدني في الأنظمة البلازمونية نانوية الهيكل لتصميم وحدة الخلية الشمسية

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Received: March 14, 2026	Accepted: April 06, 2026	Published: April 18, 2026

Abstract:
This paper discusses metallic nanoplasmonic phenomena regarding the investigation of electron oscillations in metallic nanostructures, known as surface plasmons. Surface plasmons exhibit extraordinary optical properties. Plasmons are primarily found in metals, where electrons are weakly bound to atoms and are delocalized. Electrons in a metal can undergo collective oscillations, being pulled back by the attraction of the positive metal ions from which they originated.

Keywords: Plasmons, electromagnetic wave absorbing, metamaterial, 3D power consumption, high temperature resistance, HFSS.

الملخص
تناقش هذه الورقة الظواهر البلازمونية النانوية المعدنية المتعلقة باستقصاء اهتزازات الإلكترونات في الهياكل النانوية المعدنية، والمعروفة باسم "البلازمونات السطحية" (Surface Plasmons). وتُظهر البلازمونات السطحية خصائص بصرية استثنائية؛ حيث توجد البلازمونات بشكل أساسي في المعادن التي ترتبط فيها الإلكترونات بالذرات ارتباطاً ضعيفاً وتكون "غير متمركزة" (Delocalized). "يمكن للإلكترونات في المعدن أن تخضع لاهتزازات جماعية، حيث تنجذب للعودة إلى مكانها بفعل قوى الجذب للأيونات المعدنية الموجبة التي نشأت منها.

الكلمات المفتاحية: البلازمونات، امتصاص الموجات الكهرومغناطيسية، المواد الخارقة، استهلاك الطاقة ثلاثي الأبعاد، مقاومة درجات الحرارة العالية، برنامج HFSS.

Introduction

The problem statement begins by acknowledging the significant growth in internet usage, driven by the widespread availability of tablets, smartphones, and social media. Assuming a global mobile phone user base of 8 billion people (as depicted in Figure 1), it is observed that approximately 67% utilize mobile phones, about 65% access the internet, and roughly 55% engage with social media. This indicates a substantial volume of internet traffic [24].

Figure 1: Assume that 8 billion people are use mobile phones[24].

Consequently, the internet is considered a major conduit for information. According to statistics [20], by 2030, traffic is projected to exceed 5000 Exabyte's, as illustrated in figure**2**.Given the extensive internet access points, a large bandwidth is necessitated. Furthermore, connections must be error-free, demanding very high connectivity. As a result, high-power consumption is observed, leading to demands that must be met by networks handling significant traffic.

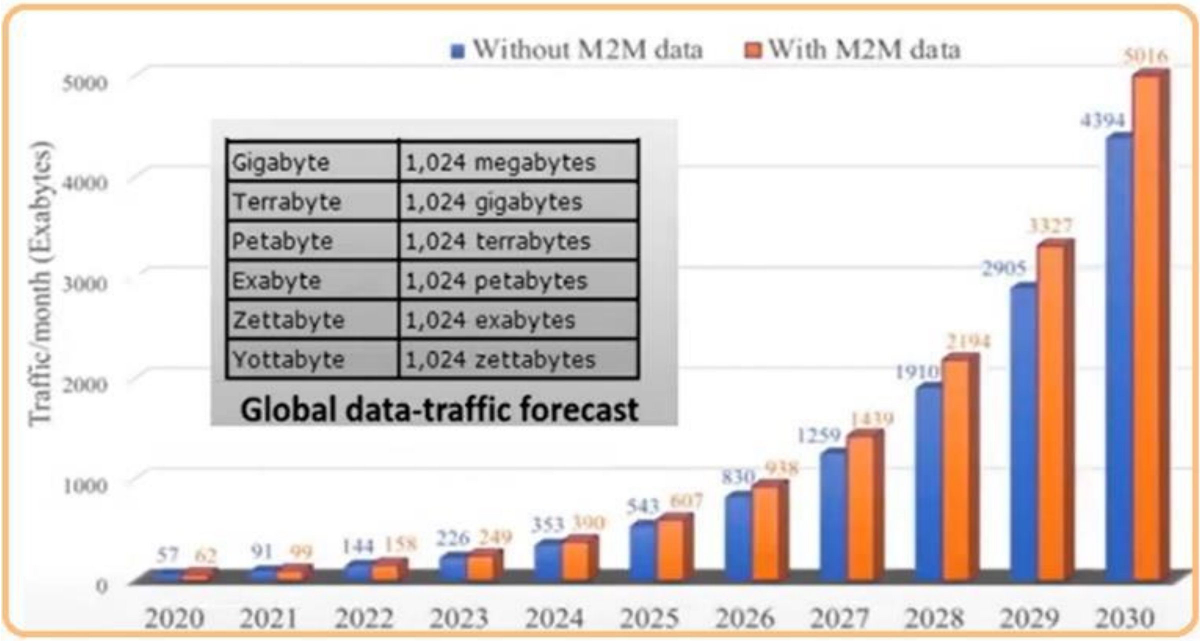

Figure 2: A according to statistics [20], by 2030 traffic is expected to exceed 5000 Exabyte's.

Integrated Circuits (ICs) are recognized as highly advanced technologies, expected to efficiently meet the aforementioned demands, particularly following the intensive integration processes applied to ICs. Moore's prediction suggested that to achieve devices with high speed and low power consumption as illustrated in figure 3 , their size should be reduced. When the size of a transistor is reduced, it becomes the primary component for IC fabrication.

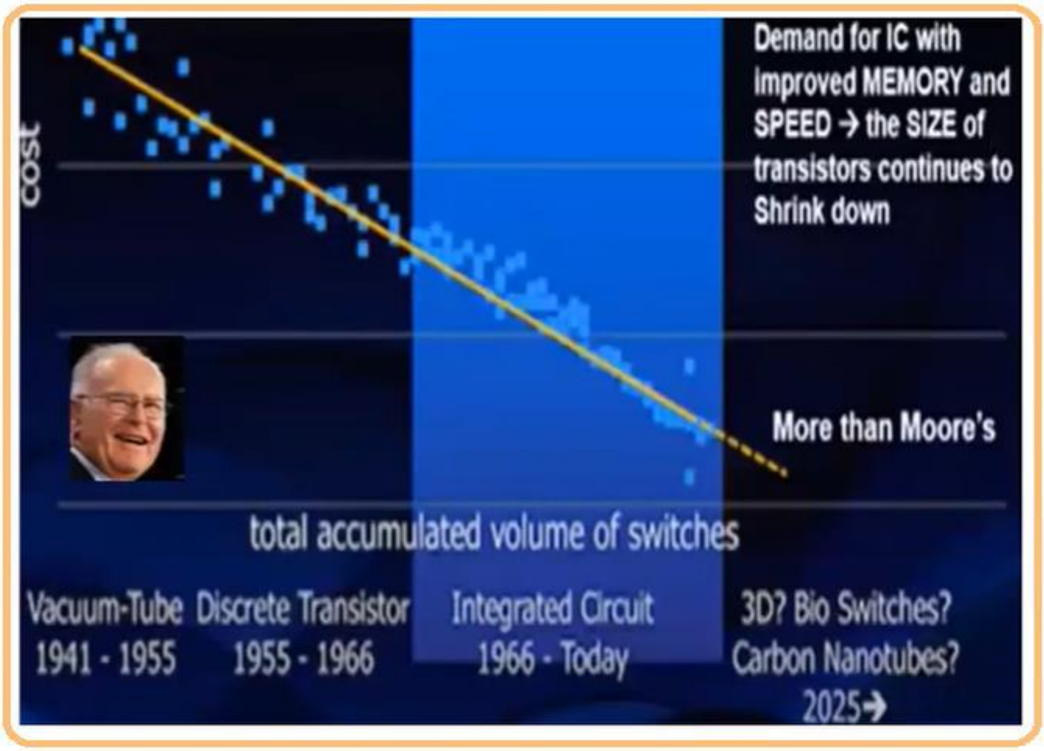

Figure 3: Dr. Moore's prediction: Transistor density on a single IC needs to be doubled every 1.5 to 2 years to scale device size and enhance processor performance [26].

This miniaturization has indeed occurred; transistors are fabricated from semiconductors located in the fourth column of the periodic table (see Figure 4).

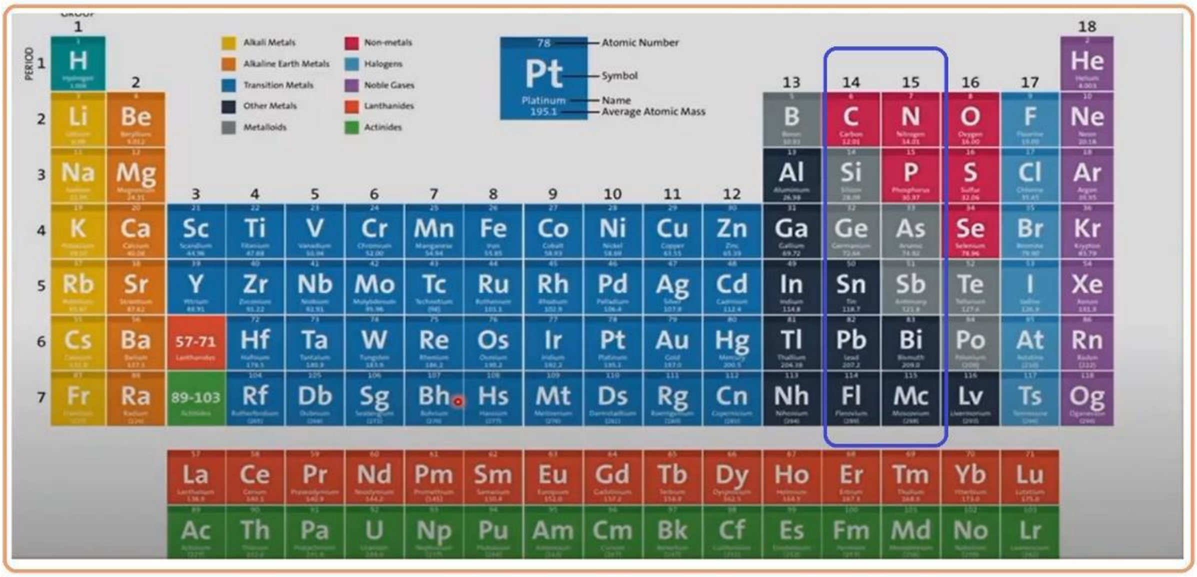

Figure 4: Natural material [5].

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During the design process, when a transistor is scaled down, the distance between the drain and source is termed the pitch, with half of this distance being the node size. The objective is to reduce the node size. Historically, the size of the node has decreased from 45nm to 5nm, as shown in Figure 5.

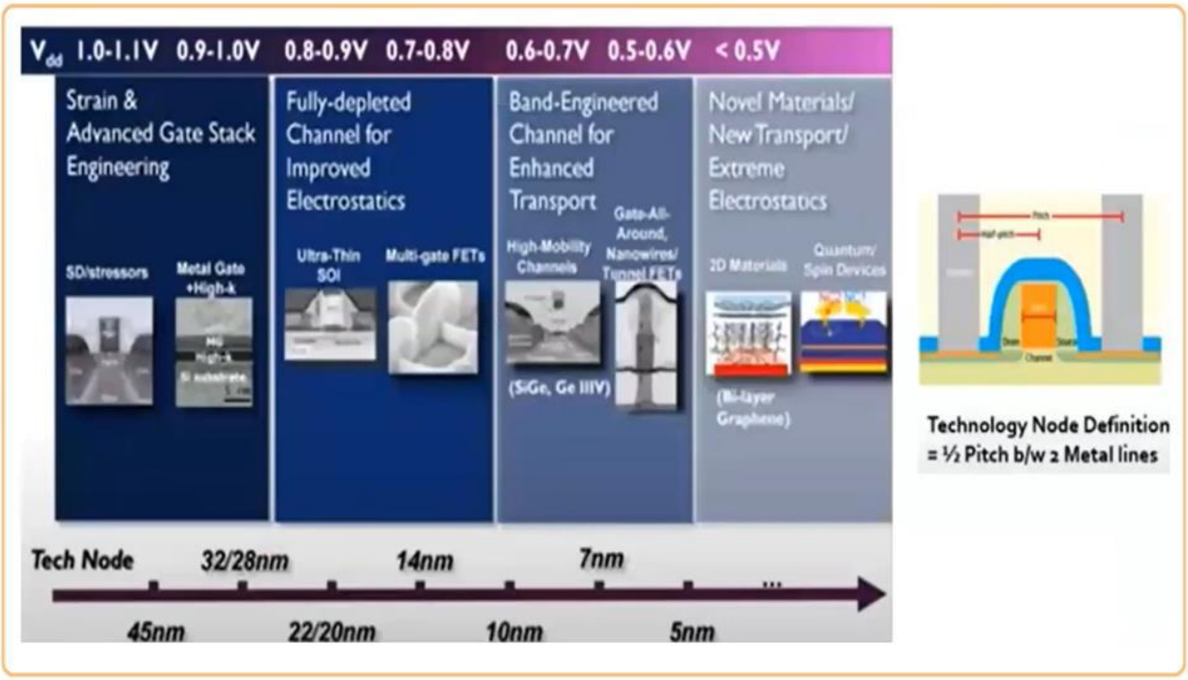

Figure 5: Transistor technology nodes: Miniaturization [25].

Reducing the node size effectively reduces the size of the entire transistor, thereby decreasing the processor voltage. This leads to a reduction in power consumption and an increase in speed as illustrated in figure 6.

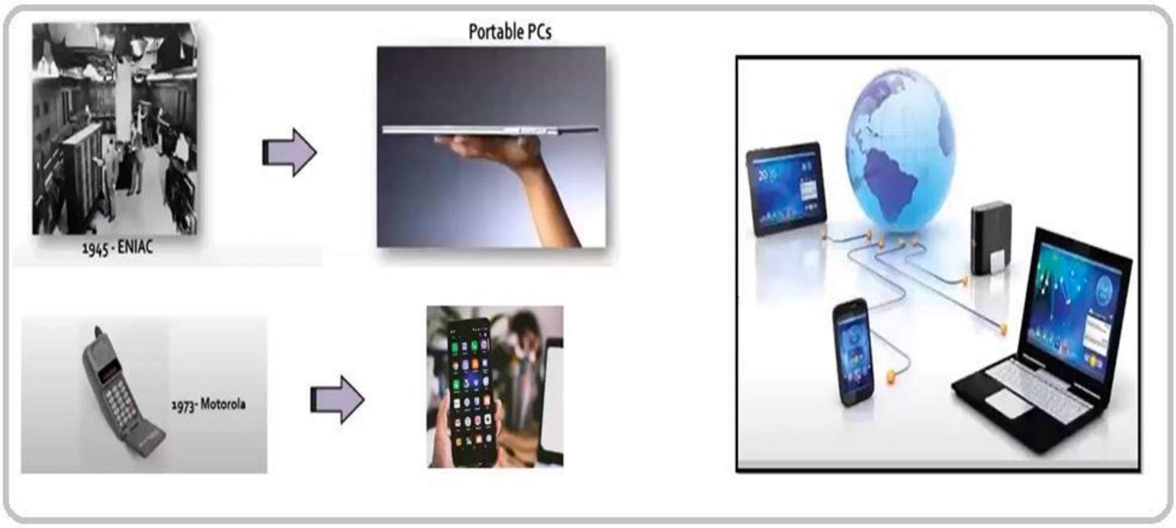

Figure 6: Miniaturization to minimize energy consumption and increase processing speed.

Therefore, IC technology has proven highly successful. Modern electronics demonstrate remarkable achievements in device integration, miniaturization, power efficiency, and information processing speed. Information and Communication Technology (ICT) devices contribute approximately 30% of worldwide electricity usage, indicating a continuous increase in power consumption [31]. A significant challenge arises as data traffic increases annually, necessitating faster data rates with miniaturized integrated circuits (ICs) [30].

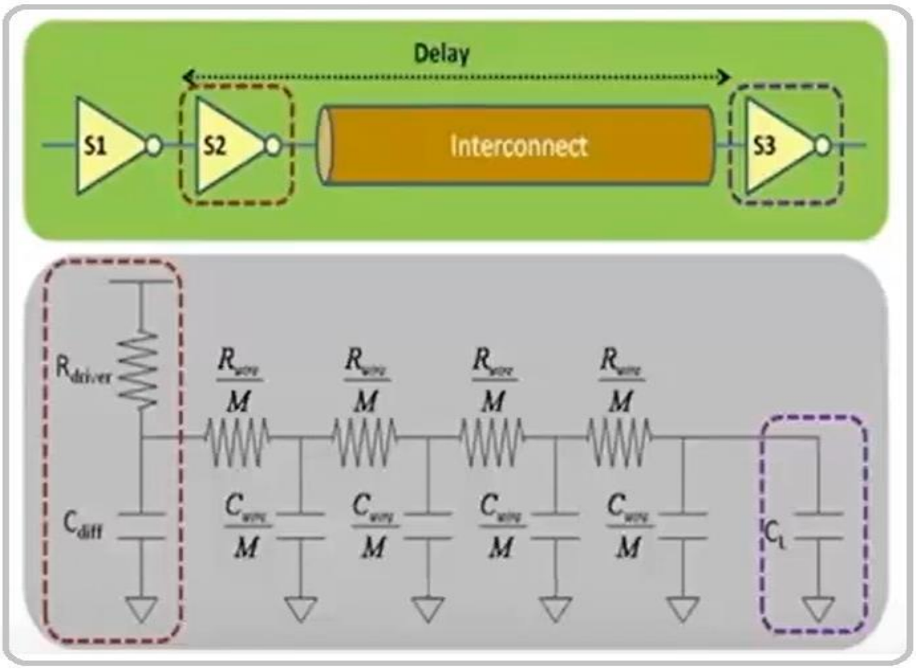

Figure 7: Interconnect equivalent RC delay mode [10].

As device size continues to decrease to enhance data processing, the Resistive-Capacitive (RC) delay of the electronic circuit becomes a major bottleneck. The speed of signal propagation in IC wiring or interconnects is dependent on the RC delay. The growing energy consumption by ICT devices proportionally increases CO2 emissions, as depicted in Figure 7. One of the most frequently visited sites, "Google.com," is estimated to emit nearly 500kg of CO2 into the atmosphere every second (see Figure 8).

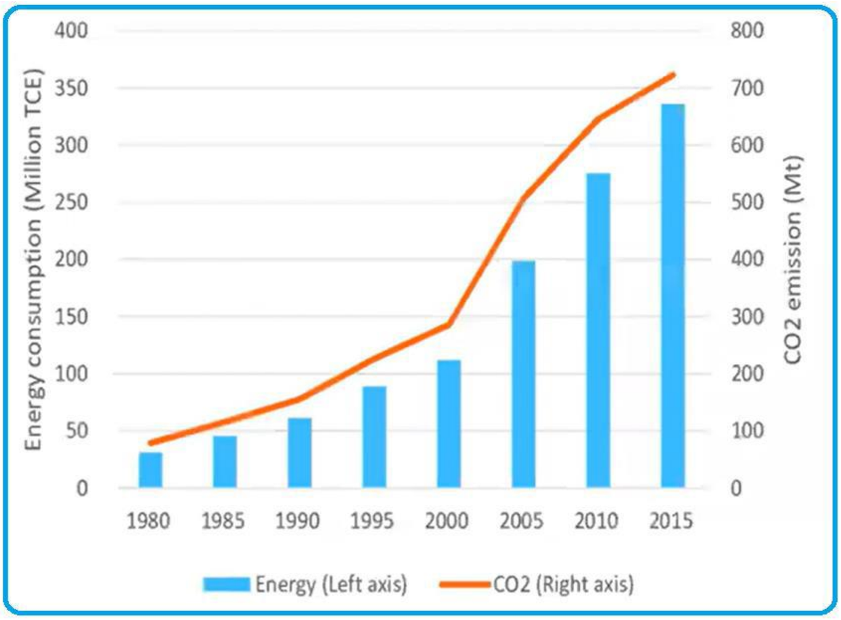

Figure 8: Data centers are likely to face challenges in limiting energy consumption (projected to increase at 10% yearly) [34].

Consequently, a new technology known as nanotechnology was developed. This involves re-engineering the shape or reshaping the composition of materials at the nanoscale.

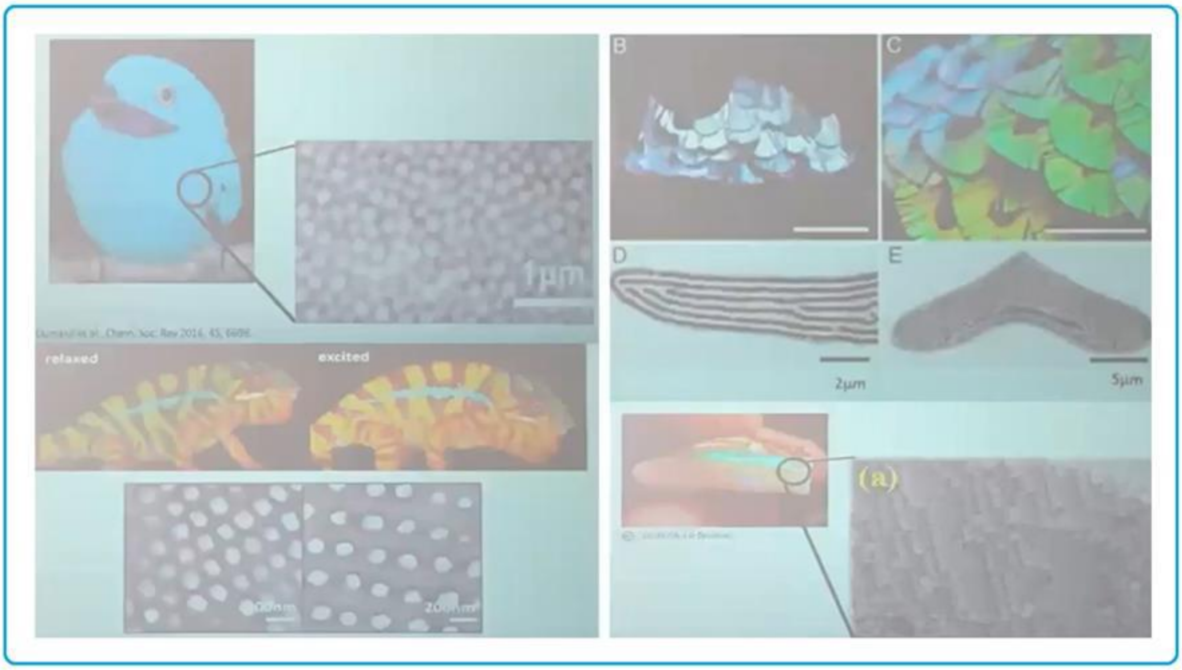

Figure 9: Nano-Materials in the Natural Words [3].

For instance, in nature, the intricate structure of a bird's small parts is composed of nanoparticles (see Figures 9 & 11). Consequently, when light rays strike at different angles, varying colors are observed in the bird's feathers.

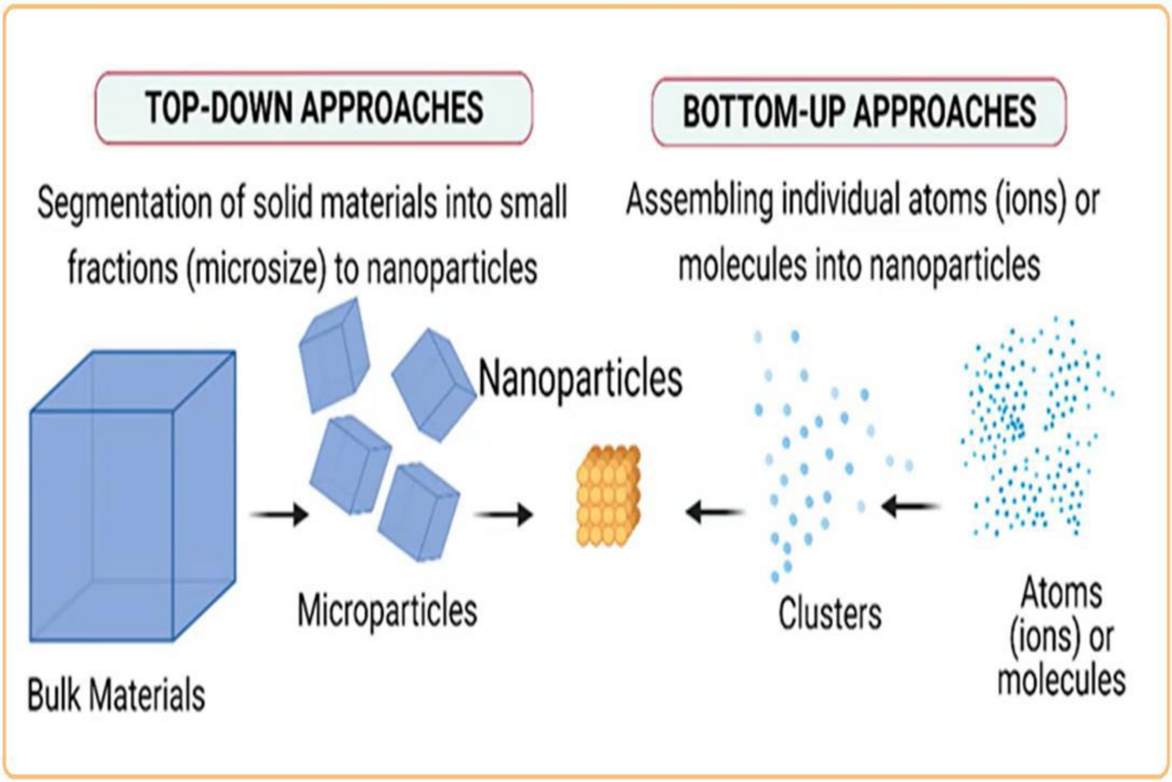

Figure 10: Design approaches [16].

Similarly, the skin of a chameleon has been found to consist of nanoparticles; when its skin is stretched, the distance between these nanoparticles changes, leading to a change in its color. This observation led to the hypothesis that by engineering materials in a specific manner, novel properties could be obtained (see Figure 10).

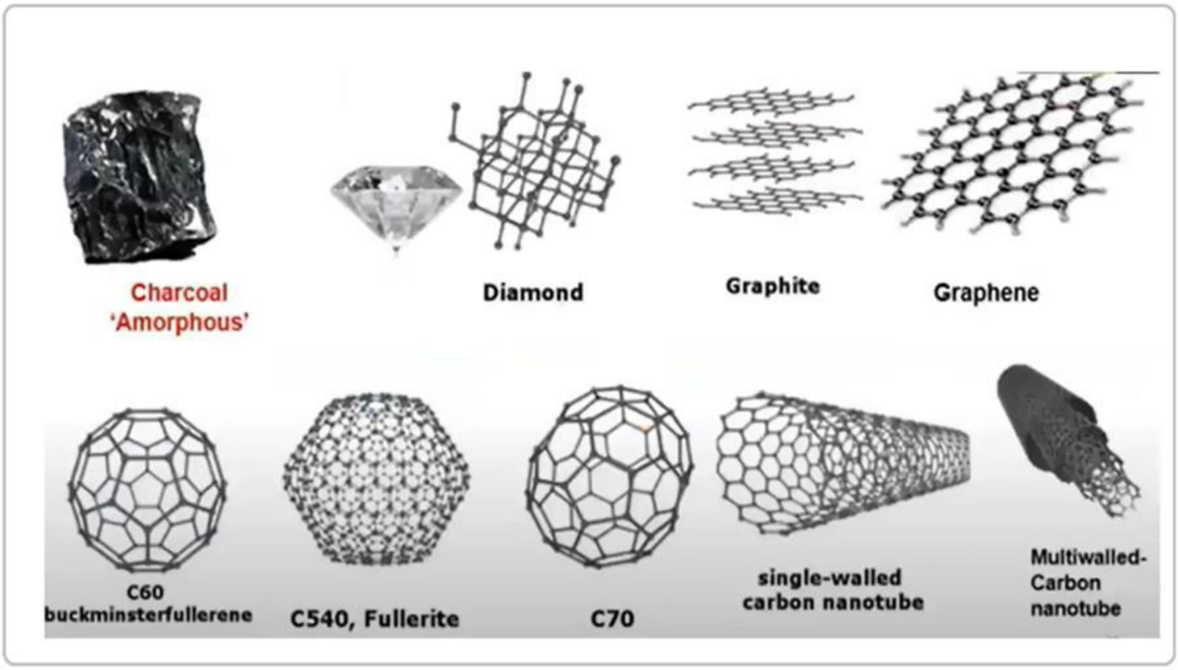

Figure 11: Example on first Approach: Carbon [16].

An example gallery of bottom-up approaches demonstrates this, achieved by sampling a set of cycles via a Metal Organic Vapor Phase Epitaxy device (see Figure 12).

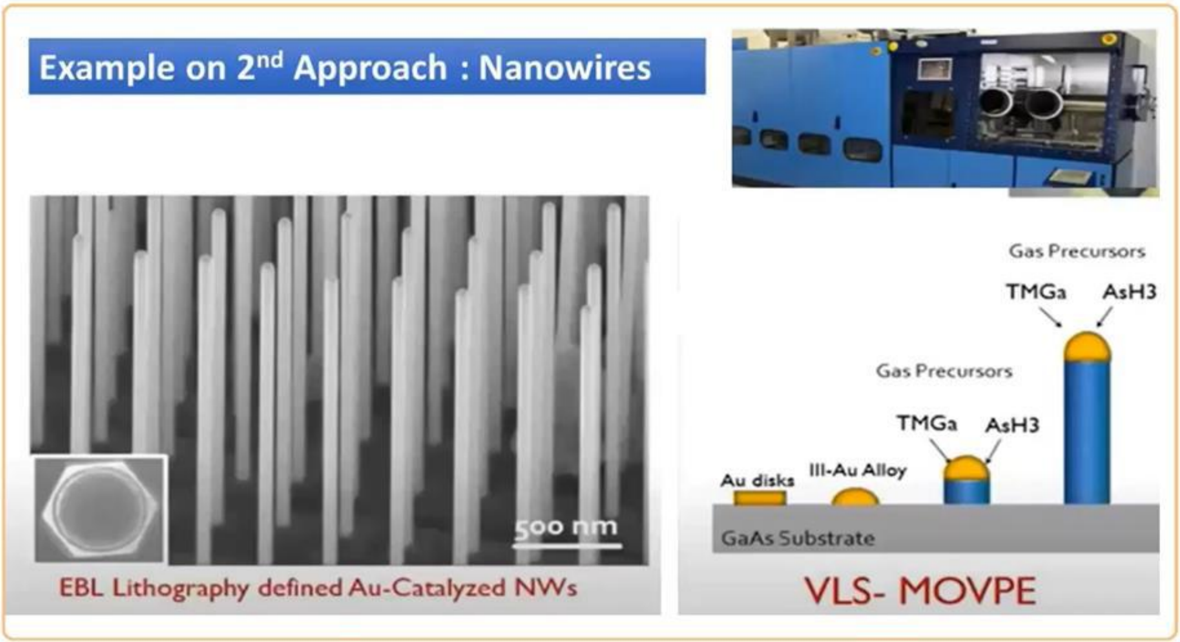

Figure 12: The objective of obtaining nanowires is to differentiate their chemical and other properties [4].

This device incorporates gallium arsenide onto which gold is precisely placed at specific points. The gold liquefies at high temperatures, after which gas is introduced into the device. This solution dissolves the gold, which then precipitates beneath it according to its concentration, transforming into nanowires. The purpose of obtaining nanowires is to differentiate their chemical and other properties (see Figure 13).

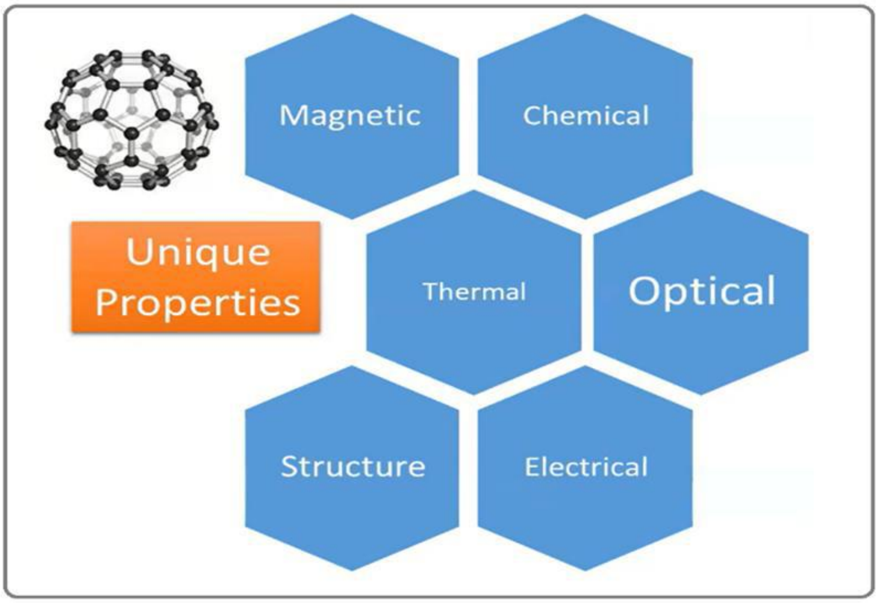

Figure 13: The purpose of obtaining nanowires is to differentiate their chemical properties.

Nanoparticle properties include a very large surface-to-volume ratio (facilitating adsorption and catalysis). Adsorption refers to the adhesion of atoms, ions, or molecules from a gas, liquid, or Nanotechnology operates at the nanoscale (nanostructures and nanomaterials) to produce new structures, materials, and devices. This technology promises scientific advancement in many sectors, including optics and Nano electronics (see Figure 14).

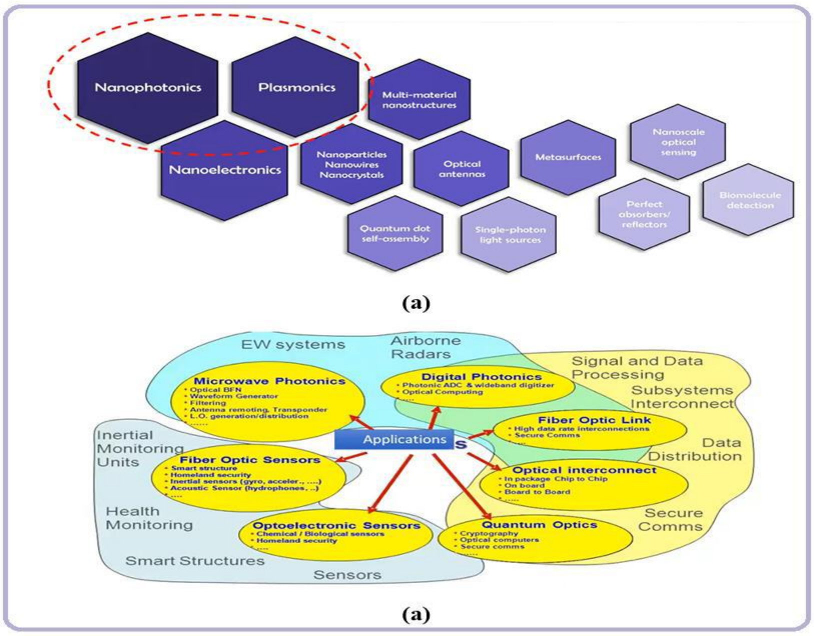

Figure 14: The technology promises scientific advancement in many sectors, including optics or Nano electronics [1].

The focus on Photonics is justified by its diverse applications, including solutions for process speed problems and power consumption. This is primarily because, in photonic systems, neither resistance nor capacitance is present (as shown in Figure 15 a-b).

Material and methods (Design Of Cell Sonar)

This paper illustrates a straightforward and physically intuitive procedure to optimize the net overall absorption of a thin-film Si solar cell across the entire solar spectrum, as depicted in the schematic Figure 15.

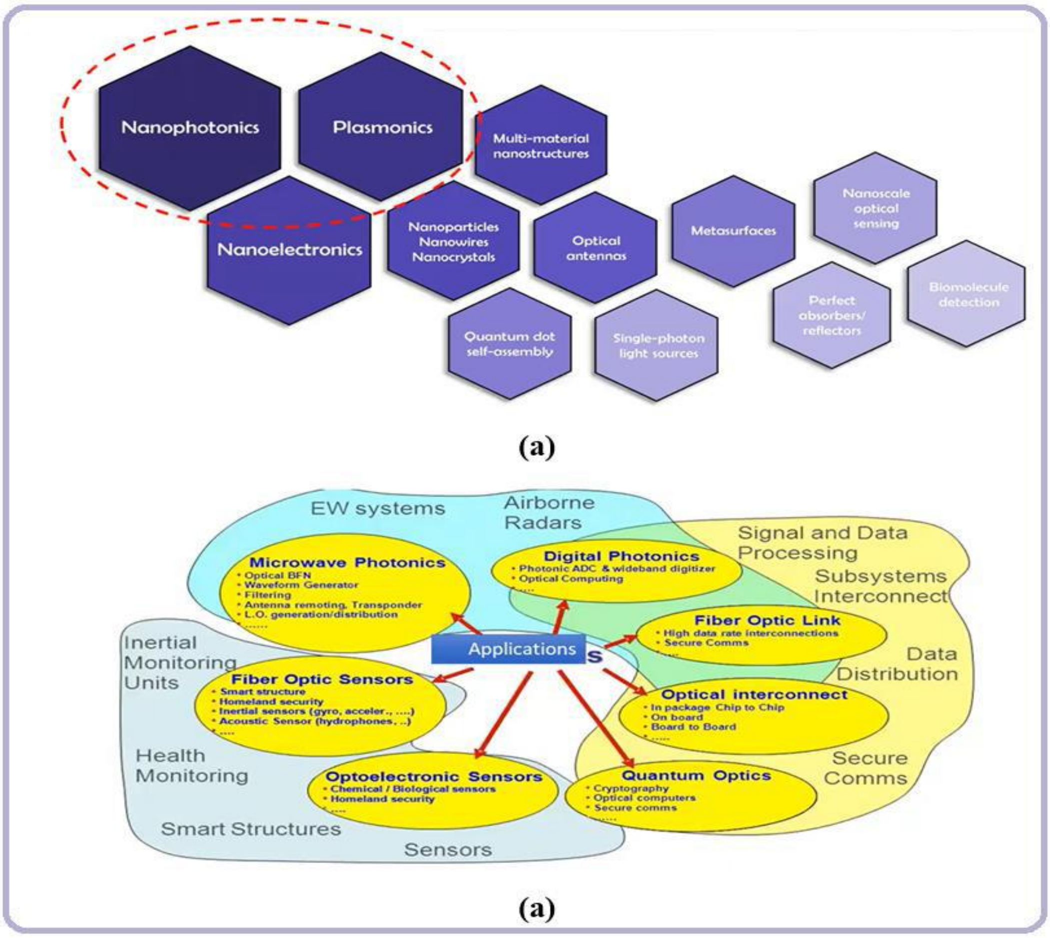

Figure 15: A schematic of the proposed Plasmon-enhanced cell structure.

Figure 15. Geometry of the same structure with a periodic array of metal strips spaced at p=312nm, a spacer layer thickness of s=10nm, and an absorbing Si film thickness equal to a=50nm. The incoming wavelengths of b) and c) λ=650nm (1.91eV) and d) λ=505nm (2.46eV) were selected to demonstrate the effects of strong near-field light concentration or excitation of waveguide modes by the strips.
Figure 16. Spectral short-circuit current density for the model cell shown in Figure 17, both with and without a Ag stripe array of a 295nm period. Contributions related to TM and TE mode-coupling and the surface Plasmon resonance of the stripes are clearly identifiable. The inset shows the enhancement in the integrated (total short-circuit current as a function

of the period of the Ag stripe array).A simple model system, consisting of a periodic array of Ag strips on a silica-coated, thin Si film supported by a silica substrate (see Figure 15), is utilized to illustrate these concepts [6].

The metal strip geometry was chosen due to its simple cross-sectional shape, which is described by only two parameters (thickness and width). These strips are capable of effectively concentrating light in their vicinity at frequencies near their surface Plasmon resonance. This resonance frequency is critically dependent on the strip geometry and its dielectric environment [38].

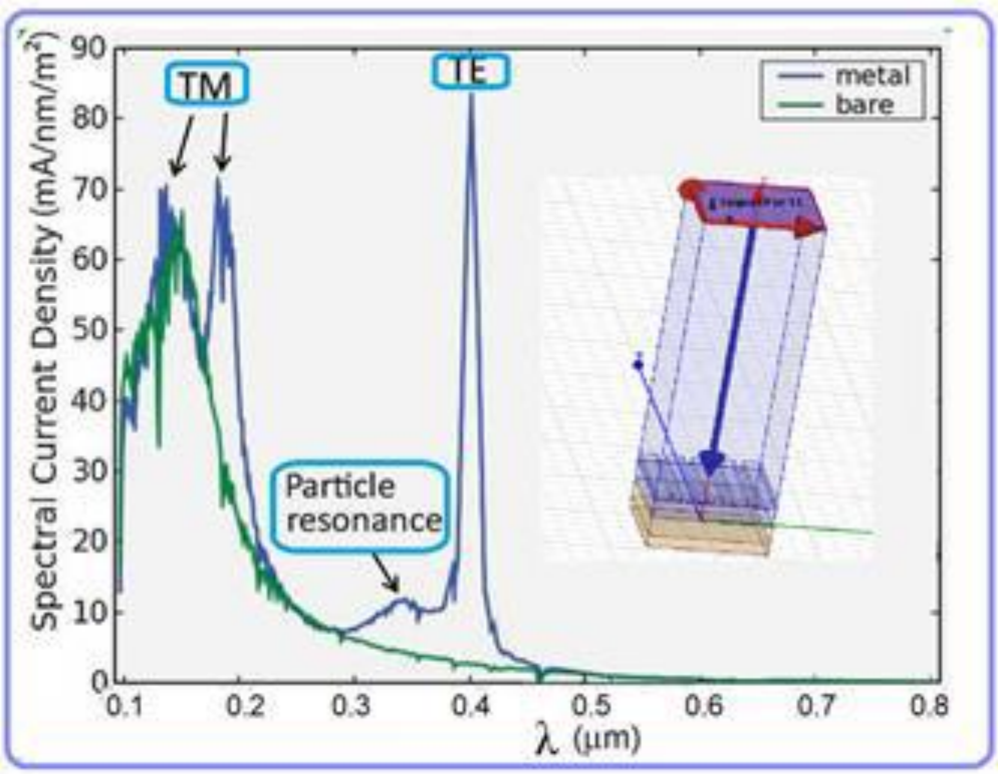

Figure 16: Contributions related to TM and TE mode-coupling and the surface Plasmon resonance of the strips can be recognized in the spectrum, and together they provide enhancements over a broad wavelength range.

From the graph, the importance of engineering large enhancements in spectral regions where both I and SR are high can be observed.

Results and discussion

In this paper, based on the preceding description, a general design strategy has been proposed for the realization and optimization of broadband absorption enhancements in thin-film solar cells using two-dimensional, periodic arrays of metallic nanostructures. By generating absorption enhancement maps versus photon energy and reciprocal lattice vector, it is straightforward to separate contributions from near-field light concentration by localized surface Plasmon resonances and enhanced light trapping by coupling to waveguide modes.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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