GaAs-AlGaAs HETEROSTRUCTURE FOR PHOTONICS

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ABSTRACT

A layer of undoped GaAs between layers of AlGaAs forms a double heterostructure. AlGaAs has a nearly identical lattice constant as GaAs, but a different bandgap that varies based on the alloy ratio of Aluminum to Gallium. The lack of dopants in the GaAs layer as well as the nearly unchanged lattice constant in the AlGaAs layers means significantly fewer collisions for carriers, and the difference in bandgap creates a quantum well that keeps carriers in the GaAs layer where they can be very easily transported. One variation of this heterostructure has been in high-electron-mobility transistors (HEMT), which provide high gain and low noise in microwave and mmWave frequency applications such as radar and satellite communications. In recent decades, the GaAs-AlGaAs heterostructure has been used in other configurations for photonic applications, such as fiber optic communications, photon detection, and photonic integrated circuits. The GaAs layers acts as cavities while the AlGaAs layers act as mirrors, creating a system able to provide resonance and gain for photons in the red and near-infrared regions around 700-900nm. This paper will focus on the physics and fabrication methods of GaAs-AlGaAs heterostructures for modern and future proposed photonic applications.

KEYWORDS

GaAs-AlGaAs, heterostructure, photonics, laser, VCSEL, MQW, photodiode, SEED.

INTRODUCTION AND HISTORY

Over the last few decades, the demand for computation – in terms of speed and volume – has exponentially increased, while the supply has begun to saturate and the bottlenecks of the technologies have become more and more apparent. Computer terminals, such as laptops, workstations, and mobile phones, are still largely based on silicon CMOS technology, but there exist many applications in the pipeline of communications and computation that necessitate more specialized devices capable of handling the increased load. For example, the switches used at server farms handle communications through fiber optic cables with switches made of semiconductor materials such as InGaAs photodiodes. [1]

Traditional electronics are based around moving charge carriers – electrons and holes – through doped semiconductor devices and metal interconnects. These charge carriers collide with each other and the dopants themselves, causing a slowdown and dissipating excessive heat. The very mechanism enabling the technology creates a bottleneck on an atomic level. On the other hand, photons subvert issues with carrier transport entirely, and under the right conditions are able to be transmitted long distances with very little attenuation and dissipating no heat.

This has created an incentive to take optoelectronics and bring them down to the density and scalability of electronics, creating the field of photonics. Photonics encompasses systems that perform electronic functions such as modulation, amplification, and transmission but with photons instead of charge carriers. A wide array of devices and device structures have been investigated over the last few decades to achieve this goal.

GaAs is a III-V semiconductor that has been in use for decades for many applications, as a faster alternative to silicon for microwave applications, as high efficiency solar cells, or a substrate for other III-V compounds. [1]

PHYSICS

Photonics

Before discussing how GaAs-AlGaAs can be used in photonic applications, it's important to cover the basic principles of photonics such as laser amplification and pumping. Photons are the fundamental quanta carrying electromagnetic energy, with energy as a linear function of its frequency. Materials can be effectively characterized by the frequencies they absorb, amplify, or pass. This is because their electrons can only exist in discrete energy states, lowered and elevated by photon interactions.

There exists three interactions between photons and electrons: absorption, emission, or stimulation. Absorption is when the photon hits an electron in a lower energy state and moves it up to a higher energy state. Emission is when an electron in a higher energy state emits a photon and moves to a lower energy state. Stimulation is when a photon hits an electron in a higher energy state, but it moves to a lower energy state, allowing the incident photon to pass but also emitting a photon completely identical to the first. This is known as the LASER effect (Light Amplification by Stimulated Emission of Radiation). [2]

If $\varphi(z)$ defines a stream of photons with frequency ν traveling in direction z, and it hits a medium with transition cross section defined by function $\sigma(\nu)$, then the probability density function of photons at that frequency being absorbed is

$$W= \varphi(z) * \sigma(\nu) \tag{1}$$

$N1$ is the density of atoms in a lowered state, and $N2$ is the density of atoms in an excited state, and

$$N = N2 - N1 \tag{2}$$

$W*N$ is therefore the net number of photons per second per unit volume. When this quantity is positive, the medium can amplify light. When it's negative, it attenuates light. When it's zero, it is transparent. [2]

In order for that quantity to be positive, the medium must be in non-equilibrium so $N2$ can be greater than $N1$, creating population inversion. An external power source, called a pump, is required to keep enough atoms in an excited state. A pump serves the same purpose as VDD in a traditional CMOS amplifier, while the incident photons to be amplified act as the signal. Materials can be pumped by either photons or conduction. Semiconductors can be pumped by charge carrier injection. When a gain medium is pumped, and photons of the right frequency hit it, an elevated electron emits two photons as it moves to a lower state, then each of those two photons hit an elevated electron, which each emit two more photons, causing a chain reaction creating a beam of coherent light emission. The gain coefficient is

$$\gamma=N*\sigma(\nu) \tag{3}$$

and the overall gain is

$$G=e^{\gamma*d} \tag{4}$$

where d is the length of the gain medium along the z-axis. [2]

This, however, does not create a terribly efficient device if the intent is to properly guide and utilize the incoming signal. To create a laser as we know it, the active medium must be placed within a resonator. When the medium is pumped and the population is inverted, it provides gain. Electrons are stimulated, cloning photons and starting the lasing process. Rather than being beamed out, the photons are kept within the medium by the resonator (e.g. a pair of mirrors). This creates a positive feedback loop, where the generated photons also pump the medium, leading to further stimulation. If the feedback loop has a phase shift of a multiple of 2π, and the gain is greater than the loss, oscillation begins, as shown in Figure 1. This is the photonic analog to Barkhausen's stability criterion. Oscillation continues, and the gain goes down until it becomes equivalent to the loss and the system is stable. [2]

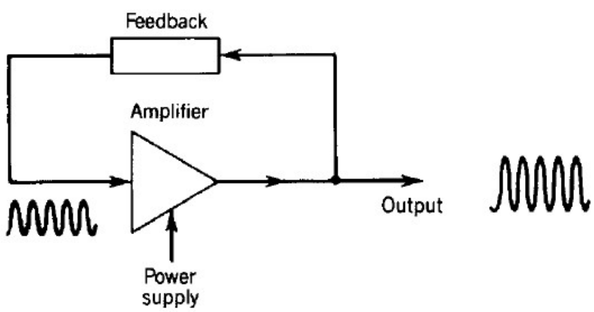

Figure 1: Laser Oscillator [2]

GaAs-AlGaAs

GaAs is a III-V direct bandgap material with a bandgap of 1.43eV, stimulation of which can be seen in Figure 2. Being a direct bandgap material means its electrons can move from the valence band to the conduction band just through photon absorption, making it an ideal candidate for applications like photovoltaic cells. GaAs has complex drift velocity; it has a higher electron mobility than silicon under low electric fields, but as the electric field increases, the drift velocity suddenly dips. Pure GaAs is also highly resistive and makes it an excellent substrate to grow other III-V compounds on. [1]

One material that can be readily grown on GaAs with great success is AlGaAs. AlGaAs has a lattice constant that is under 0.14% off from pure GaAs [3], so aluminum can be inserted without breaking the structure. While they have nearly equivalent lattice structures, AlGaAs has a wider bandgap than GaAs. Interestingly, that bandgap is dependent on the ratio of aluminum to gallium, which means that the bandgap can be controlled and specified in the fabrication process as needed. AlGaAs can also be doped as needed to modify its energy band.

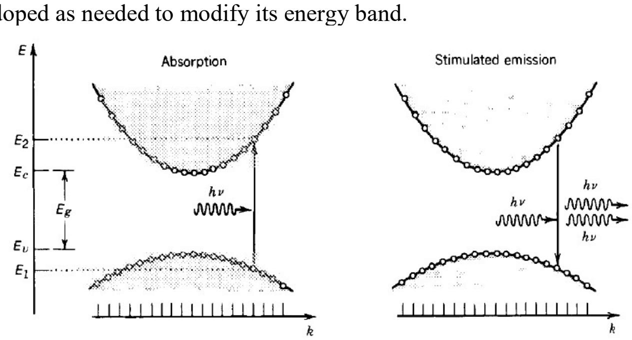

Figure 2: Absorption vs Stimulated Emission [2]

When AlGaAs is placed next to GaAs, a heterostructure is formed. The difference in bandgap is large enough that in equilibrium it is difficult for electrons in the GaAs structure to move over to the AlGaAs structure, creating a quantum well. [1] This heterostructure creates ideal conditions for high speed circuits in traditional electronics such as the High Electron Mobility Transistor (HEMT). In an HEMT, the electrons from the doped AlGaAs region fall into the GaAs's quantum well and cannot go back. Once there, they're in a region with high electron mobility as previously mentioned, higher than in typical MOSFETs because there are no dopants breaking the lattice structure for the electrons to collide into. [1]

GaAs-AlGaAs Multiquantum Well Heterostructure

GaAs can also be used effectively as a laser gain medium. In semiconductors, photons interact with electron-hole pairs, which are either generated or recombine. Absorption causes electron-hole pair generation, electron-hole pair recombination emits a photon, and electron-hole pairs can recombine by stimulation and clone a photon to amplify light. The statistical probability of absorption and stimulation is determined by the quasi-Fermi levels of the semiconductor. [2] Photons with an energy greater than the gap between the conduction and valence quasi-Fermi levels will get attenuated. Because a semiconductor in thermal equilibrium has its quasi-Fermi levels both equal to each other, all photons will be attenuated and it cannot amplify light. The semiconductor must be brought out of thermal equilibrium to create a gap between the quasi-Fermi levels, and furthermore that gap must be greater than the bandgap energy because any photons below the bandgap energy will simply pass through. This creates an inequality that defines the frequency range that the semiconductor can amplify:

$$Eg < h\nu < Efc - Efv \quad (5)$$

GaAs's E-k relation is parabolic, and its quasi-Fermi levels are determined by external pumping, so range of frequencies the medium can amplify can be tuned by a rather simple relationship between the pumping and quasi-Fermi levels. This external pumping can be achieved either with photons or electrically injecting current through a pn junction. [4] If the incident photons are travelling in direction z, and electric current passes perpendicularly through a pn junction formed by GaAs in the x-y plane, the gain coefficient increases as the thickness in the direction of current in the optically active portion decreases. Therefore, it is beneficial to reduce the thickness. However, reducing the thickness too much can lead to carriers diffusing out of the region before they can recombine. [2]

This is where AlGaAs plays a pivotal role in the functioning of GaAs as an active laser gain medium, especially as dimensions shrink for nanoscale applications in photonics. A thin layer of GaAs is sandwiched by two layers of AlGaAs, one on either side, turning the active gain medium into a quantum well. This keeps the electrons from diffusing out of the medium. With the right structure and feedback, the AlGaAs acts as a resonator to make the GaAs-AlGaAs double heterostructure act as a laser. [2]

The active medium has higher gain the thinner it is, but this also means reducing the total number of photons that can actually pass through. To get around this, several alternating layers of GaAs and AlGaAs can be put together to form what is called a multiquantum well (MQW). Doping the GaAs with either donors or acceptors, and/or modifying the ratio between Al and Ga in the AlGaAs layers allows tuning of the MQW's characteristics during fabrication. [2]

FABRICATION

Epitaxial Growth

A means of growing a GaAs-AlGaAs heterostructure is through epitaxy, in this case more specifically molecular beam epitaxy (MBE). In epitaxy, each layer is grown directly on the layer beneath it, with the previous layer acting as a seed for the subsequent layer. The first step is always a clean crystal substrate to grow the desired layers on. In a HEMT, for example, a relatively thick layer of silicon (300-500um) is grown, followed by a 1um GaAs layer and AlGaAs in the tens of nanometers. [5]

An important part of epitaxial growth is lattice matching. As each layer is grown, the goal is to be as free from defects and strain points that can crack and completely ruin the device's operation. If the lattice constants of two crystals matches closely, they can be grown alongside each other and the bonds at the heterostructure layer will remain even. The lattice constant of GaAs is 5.6533Å while the lattice constant of AlGaAs is 5.6548Å. This close lattice constant allows for a clean heterostructure. [3]

In contrast to the other two major forms of epitaxy, liquid-phase epitaxy (LPE) which is grown in liquid, and metal-organic chemical vapor deposition (MOCVD) which is grown in gas, MBE is a type of epitaxial growth under ultrahigh vacuum (UHV). MBE's advantage is that it's far and away the best for ultrathin deposition in uniformity and thickness control.

In MBE, the substrate is held rotating on a heater in a UHV chamber. It has multiple beams pointed at it, each of which releases a different element, sourced from a heated crucible. The crucibles heat the elements up enough such that their vapor goes to the beam, and controlled shutters allow tiny amounts of each to go through an effusion cell. These vapors then condense on the substrate as a thin crystal layer. A reflection high-energy electron diffraction (RHEED) is used to monitor the deposition on the substrate while the growth is happening, giving the process a highly precise degree of feedback throughout the entire process. Figure 3 is a drawing of a MBE system.

With GaAs-AlGaAs specifically, the group V As is more volatile than the group III Ga, which leads to As continually evaporating off the substrate as it is being deposited. The way to compensate for this then is to simply beam more As and let the Ga deposit and bond with arsenide molecules as they deposit and form a chemical bond until the full structure is grown. GaAs is grown on a substrate in the range of 600-650˚C while AlGaAs is grown above 700˚C to prevent the oxidation of Al. It is also during this process that the exact alloy ratio between Al and Ga can be controlled. Dopants can also be added during MBE, with silicon being a common impurity. [6]

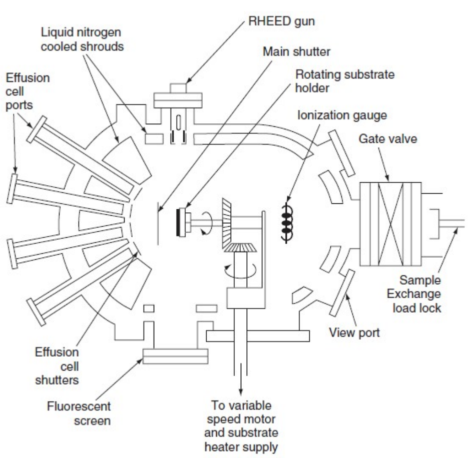

Figure 3: Molecular Beam Epitaxy system [3]

Impurity-Induced Layer Disordering

Another form of fabrication and doping is impurity-induced layer disordering. This is a technique in which the layers are fabricated using MOCVD, and then a dopant such as silicon or zinc is diffused into the material. GaAs is fabricated, and then instead of AlGaAs, what's formed is AlAs and GaAs together as an alloy. When zinc is diffused into AlAs-GaAs, it creates vacancies that the Al and Ga try to fill as the zinc moves through, transforming the alloy into a bulk AlGaAs crystal layer. [6]

APPLICATIONS

Photodetector

Photodetectors are devices that take advantage of the photoeffect. It works in reverse of stimulated emission, rather than an external field being applied to pump electron-hole pairs which are then recombined by photons for stimulated emission, photons hit ground state electrons to create electron-hole pairs which are then swept away by the applied electric field. Thus, photons "generate" electrons and current. [4]

The GaAs-AlGaAs heterostructure can be used to create a photodiode. While GaAs has a peak sensitivity around 800nm (near infrared), AlGaAs is highly sensitive around the 400-500nm (violet). By creating a heterostructure where the p-n junction depletion region is made up of both compounds, a wideband photodiode can be created across the visible light spectrum. The structure of such a p-n photodiode is shown in Figure 4. [7]

contact layer p^+ GaAs (Be)	$2 \cdot 10^{18}$ cm^{-3}	45 nm
"window" p^+ AlAs (Be)	$2 \cdot 10^{18}$ cm^{-3}	50 nm
p $Al_{0.35}Ga_{0.65}As$ (Be)	$5 \cdot 10^{17}$ cm^{-3}	500 nm
n $Al_{0.35}Ga_{0.65}As$ (Si)	$5 \cdot 10^{17}$ cm^{-3}	500 nm
buffer n^+ GaAs (Si)	$1.5 \cdot 10^{18}$ cm^{-3}	200 nm
substrate n^+ GaAs (Si)	$1.5 \cdot 10^{18}$ cm^{-3}	400 µm

Figure 4: pn photodiode cross-section [7]

A practical application for this is with a scintillator. Scintillators are commonly used to convert high frequency cosmic rays into visible light. This can then be picked up by a photodiode to convert to a signal to image the cosmic radiation hitting the Earth, a vital scientific task. The resulting GaAs-AlGaAs junction creates a situation where because each has a peak on an end of the visible spectrum, the photosensitivity across the visible spectrum looks like an upside-down parabola with a peak at 570nm (yellow-green). [8]

Vertical-Cavity Surface-Emitting Lasers

Vertical-cavity surface-emitting lasers (VCSELs) are one of the major types of semiconductor lasers. VCSELs can be fabricated in a variety of sizes, from millimeters down to micrometers in diameter, for a variety of applications, such as laser printers and sensors and communications. As previously shown, a semiconductor laser can be created by beaming photons into a pumped medium, emitting stimulated photons parallel to the direction of the incident photons, and further amplified by reflectors in the form of a quantum well. In a VCSEL, the stimulated emission occurs perpendicular to the stacked layers instead. [3]

An important feature of a VCSEL is a distributed Bragg reflector (DBR). A DBR is made of several layers of alternating materials with different refractive indexes. The right combination forces a narrow band of wavelengths to hit quantum wells and return back. The GaAs-AlGaAs heterostructure MQW is very effective at acting as a DBR. Three different examples are shown below in Figure 5. [9]

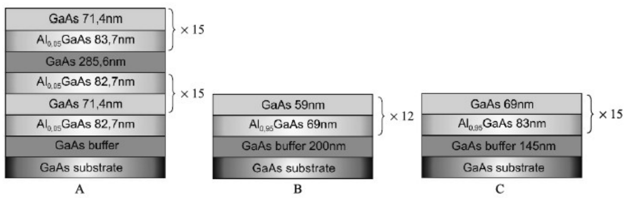

Figure 5: Layer widths for DBRs [9]

Another material like InGaAsAl-InP is used as the active medium, and is pumped by an external electronic source. VCSELs are key to future optical interconnects, as they are comparatively low power, highly efficient, and very fast. Furthermore, while they require lots of expensive equipment and processes to produce and are more expensive per laser, because the incident beam is perpendicular to the 2D growth array, a higher density of them can be grown in a given area, and they can be tested as they're grown layer by layer. On the other hand, "lateral" lasers need to be fully grown before they can be tested, allowing for large quantities in a batch to go bad without knowing throughout the process. [10]

In recent year, there has been an effort to further improve the GaAs-AlGaAs heterostructure DBR through the use of photonic crystals. Implanting photonic crystals, regularly spaced etchings deposited laterally on each plane, helps further control and confine incident photons, improving the DBR's ability to reflect light in a concentrated beam. An advantage of this method is that unlike other methods of improving the DBR such as wet oxidation, etching photonic crystals works independent of the structure being etched. [9]

Self Electro-Optic Effect Device

The basis of any digital system is a switch, enabling digital communications by CW (continuous wave). In optical systems, this means using a modulator to switch a beam of light on and off, transmitting 0's and 1's. A GaAs-AlGaAs MQW makes for an excellent modulator. When an electric field is applied perpendicular to the structure, it looks like a reverse biased pin diode and modifies the absorption of the medium. It becomes a modulator when hit perpendicularly with a beam of light in the right frequency, and emits perpendicularly. This principle is the quantum-confined Stark effect. [12]

If there is a reverse voltage across the GaAs-AlGaAs MQW with a resistor in series, the structure will have some nominal absorption. When it's hit with light, charge flows just as though it were a photodiode. That creates a voltage drop across the resistor, meaning there's less voltage across the pin diode. This leads to an increase in absorption, leading to an increase in absorption and so on as a positive feedback loop until the MQW reaches peak absorption and the bias across it is 0V and the original pump no longer has to provide anything beyond a minimal amount of power to keep the pin diode in a low voltage state. The original power source can reinject energy and decrease the absorption, reversing the positive feedback loop and setting the device to a high voltage state. This means the device is bistable, and is called a self electro-optic effect device (SEED). [2] The most basic case is referred to as an R-SEED because of the resistor in series with the pump source, shown in Figure 6.

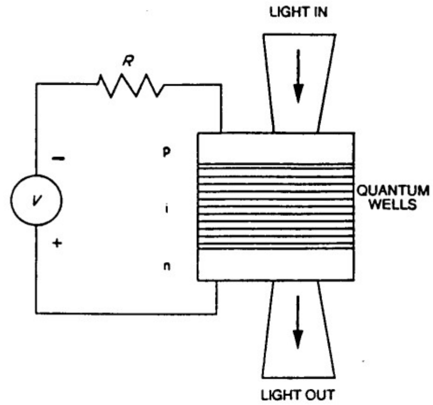

Figure 6: R-SEED [12]

Where the SEED becomes interesting is when the resistor is replaced with a AlGaAs photodiode, a D-SEED. The bistable state of the GaAs-AlGaAs MQW is set by light hitting the photodiode load. The MQW absorbs and emits infrared light based on how the pin load diode is hit with a red control light. An interesting way to operate this combination is by simultaneously turning the input infrared light and the red photodiode control light on or off, creating latching memory. This configuration can latch a state for up to 30s with absolutely zero power. [12]

After this there's S-SEEDs, symmetrical MQW diodes, both being operated optically in parallel but electronically in series, acting effectively like a true three-terminal digital device. From here it is possible to create actual logic gates with an integrated array of devices. There is also AW-SEED (asymmetric-well SEED), T-SEED (transistor-biased SEED), and F-SEED (field-effect transistor SEED). [12]

The F-SEED or FET-SEED has been the subject of a lot of research. For one, it is comparatively simple to fabricate. A planar MOSFET structure can be fabricated on top of a GaAs-AlGaAs MQW just as if it were being fabricated on top of a silicon substrate. The drain is placed on top of a doped GaAs layer. When the gate of the MOSFET turns on, the MQW outputs the light beam that appears at the drain. This function at the gate can also be controlled by an external source of light. Blocks of logic created with this technology are known as "smart pixels". [13]

SCALING AND LIMITATIONS

As explained previously, the gain coefficient of a double heterostructure and thus MQW increases as the width of the active medium decreases. However, at a certain point, the very insignificant strains in the epitaxial growth between layers causes alloy clustering. Alloy clustering prevents any further improvement in performance from decreasing width as it approaches 50Å. [6]

In photodetection, the MQW has a high dark current density, meaning it's rather noisy and deteriorates performance in switching applications. Noise in the case of photodiodes is when carriers are transported even with no incident photons. It is possible to overcome these issues by biasing it and bringing down the temperature to 77K (liquid nitrogen) and then stimulating it with a local oscillator, meaning it makes for a decent heterodyne. [8]

DISCUSSION

GaAs-AlGaAs has long held dominance in the field of microwave circuits and MMICs, [5] and is one of the most well understood semiconductor heterostructures. This paper set out to investigate if the quantum well properties, direct bandgap, and high carrier mobility made for a strong case as both photoemitter and photodetector, especially as the modern world has shrunken such devices down to be integrated with electronics, which have begun to hit a wall. We've presented a few different devices, all of which have been researched extensively. What concerns us is the longevity of any of these technologies/applications in the research world.

For example, the SEED devices appeared to be the subject of much research in the late 1980s through the 1990s, primarily by Professor David Miller of Stanford, whose work is referenced throughout this paper. Some of the SEED configurations, like the S-SEED were capable of recreating conventional digital logic through the use of photonic controllers and electronic power sources. Research into F-SEEDs went through the 2000s, being used in what is referenced to as "smart pixel" arrays. After this, there was virtually no references to SEEDs that we could find.

The pin photodiode structure goes through a similar process. There is vibrant research through the 1970s, 1980s, and 1990s, but interest soon disappears. We must ask the question why? For the photodiode and VCSEL (though there is some recent research in improving the DBR structure), it seems as though all the theoretical and practical limitations have been researched and understood, and all applications found. While VCSELs with the GaAs-AlGaAs MQW DBRs themselves are no longer really the subject of research, what is very actively being researched is their use in "Time of Flight" sensors and LIDAR. [11]

SEEDs on the other hand we believe went obsolete. Their future purpose was to achieve the goal of photonic integrated circuits that could mimic digital circuits. It seems like what happened is that InP-based compounds, particularly InP-InGaAsP , overtook GaAs-AlGaAs in terms of speed. While GaAs-AlGaAs based circuits were shown to switch up to hundreds of Mbps, InP-based circuits have enabled data rates well into to Gbps region, enabling our modern fiber optic communication systems.

Interest has seen a resurgence recently, though, in the form of nanowires. GaAs-AlGaAs nanowires are under research for photodetection [14], lasers, and optical waveguides. [15] Whether these technologies keep up with other optical technologies and help enable the next leap, quantum computing, is to be seen.

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