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Module

Scientific English

Scientific Texts and Exercises

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Preface

In the last century, the number of scientific papers written in English has started to outweigh the number of papers written in the native language of the researcher. For this reason, having a knowledge of English is incredibly important to those working in the scientific field.

The use of English as an international language of science is by now well documented and very important.

The present scientific English course work on understanding and expression on short and long scientific documents relating to technological domains and scientific research.

This course is an initiation to scientific communication in English. Through different tests, students will learn how to use the main tools of scientific communication in English, such as :

1. Understanding scientific texts and research articles :

Understanding of scientific works (Structure, Analysis, paraphrase and summary of a scientific text).

2. Writing an abstract by using different types of transitions and connectors :

To do this, the students will have to apply a method consisting in summarizing in a very concise but precise way the different parts that conventionally make up a scientific text, namely: introduction, material and method, results and discussion.

3. Oral training through presentations followed by discussions :

The goal here is not to improve grammar skills or English accent, but rather to be able to communicate with other people (English or non-English speakers) to talk about science using English as an international tool, without being inhibited by their level. To practice, the students will for example introduce themselves in front of the class, participate in discussions, debates or presentations of scientific articles.

The course also aims at reassuring students and encourage them to use english to discuss scientific topics with other people, even if their English level is not very good.

Chapter I

Connectors in English Grammar

1. Introduction

Connectors in English grammar are basically conjunctive words that are used for connecting similar elements present in a sentence. There are different connectors in English that can be used for expressing your thoughts in a better way. Smart use of linkers can omit the requirement of single sentences and help in connecting the sentence in a more logical way.

In this section, you will not only know the various kinds of sentence connectors but will also get simple linker examples that will help you in understanding the meaning of connectors. So, let the journey begin.

2. Importance of Connectors in English Grammar

Connectors are important because they make any phrase more logical and understandable. As a result, any transcriptionist who is transcribing audio files or other taped materials should constantly be conscious of the use of conjunctions. Consider the existence of the coordinating conjunction to denote reason in the following sentence: “I walked to the office because my car was being repaired.”

While it may be tempting to add or change terms to make a phrase appear more genuine and proper, transcriptionists must resist the temptation since some contractors are passionate about the language they record or use. What a transcriptionist can do is transmit the proposals that the contractors have in mind. Respect is noticed and rapport is developed in this manner.

3. Types of connectors

There are different types of connectors in English and each of those has a different use. So, how to use connectors? Let’s check all of those sentence connectors and the examples.

3.1. Cause and Effect Connector Words

Cause & effect sentence connector words	Example of linkers in English grammar
Therefore	I slept very late last night, therefore, I missed the morning prayer.
So	The blue bag was full so he kept the packet in the yellow bag.
Because	I ran because I was afraid.
Thus	We have failed. Thus we have to take the consequences
Hence	He is looking for a formal trouser because he has an important meeting tomorrow.

Due to	The match got cancelled due to the heavy rain.
As a result	As a result of the heavy rain, the match got cancelled.
Consequently	I got stuck in the traffic consequently I missed the flight.
Since	Since she loves ice cream so much, I decided to give her an ice-cream printed dress.
Seeing that	Seeing that he was losing the fight, he started blaming her mother.
On account of	Both the siblings were mentally unstable on account of their disturbed childhood.

3.2. Contrast

Logical connectors to show the contrast	**Sentence Linkers examples**
But	I wanted to go swimming but I am so tired.
However	The film received good ratings; however, it was very long.
On the other hand/ on the one hand	I was eager to join them for the vacation but on the other hand, my exam dates were getting closer.
Otherwise	Remind them beforehand otherwise, they might leave without taking the tickets.
Unlike	Zoey loved hot chocolate, unlike John.
Conversely	Zoey may not perform up to the mark in science subjects, but conversely, he has an impeccable hold in literature.
At the same time	She felt guilty and depressed at the same time.
In spite of	In spite of heavy rainfall, he took out his scooter and headed towards the hospital.
Despite	She kept on arguing despite her mistake.
Even though/ Although	He could manage the cooking part even though that would not taste awesome.
Still/ Yet/ Nevertheless	They are still present. I have not received it yet. What you said was right but nevertheless harsh.
Even so	He had a headache but even so, he went to pick her up.
On the contrary	Mother thought John was studying but on the contrary, he was sleeping.
In contrast	Rehan Infotech made a profit of Rs. 5 Crore in contrast to last financial year’s loss of Rs. 10 Lakhs.
Whereas	All of her daughters are engineers whereas the younger one chose to be a teacher.

3.3. Advanced Connectors

Advanced connectors	Use of linkers in sentences
In addition/ besides	The umbrella will protect you from the Sun, besides it will also come handy if rainfall starts.
On top of that	And on top of that, you will also get incentives.
Furthermore	He was tired and hungry furthermore he was ill.
Moreover	You have to cook lunch and moreover that you also have to go to the market in the evening.
What’s more	What’s more, now you have all that is required to have a wonderful vacation.

3.4. Connectors of Sequence and Conclusion

Sequences, conclusion and time connectors	Example of connector words in sentences
Later	Later, it all got resolved.
After	He also left after his wife.
Before	You have to try before coming to a conclusion.
Then	Once you reach the office, then make a call to the supervisor.
Next	The next episode is going to be very interesting.
Soon	They are soon to graduate.
Finally	Finally, the war came to an end,
Second/ Secondly	Secondly, you have to manage the team.
At first sight	At first sight, he appeared to be very arrogant.
First	First, you should go to the washroom and take a bath.
First of all	First of all, they are not my family and I can not be held responsible for their immature behaviour.
In the first place	In the first place, take care of the pets and then do the rest of your work.
To start with	To start with, I asked her to tell us about her hobbies.
Lastly	Lastly, we had our dinner and left.
And finally	And finally, the day of the verdict came.
In conclusion	In conclusion, it is always better to take prevention than cure.

3.5. Purpose

Most common connector words	Linkers example
In order to	In order to prove him wrong, he started shouting.
So as to	You have to study hard so as to improve your career.
So that	Give me your resume so that I can forward it to the right department.

In order that	I want to finish my work today so that I can spend my weekend relaxing.

3.6. Example Linkers in English Grammar

Example sentence connectors	**Linkers example**
For example	For example, take the rising graph of air pollution.
For instance	I like a few vegetables, for instance, potato, cabbage etc.

3.7. Opinion English Connectors List

Different opinion connectors in English	**Use of linker words in sentences**
To tell the truth	To tell the truth, I didn’t like the show at all.
Personally	The show must go on, personally I think so.
To be honest	To be honest, I don’t support the idea of destroying her career.
I think that	He has run away, I think.
It is true that	It is true that a lot of hard work has been put in here but I really can’t see any reflection of that.
I agree	I agree with her decision.
As far as I am concerned	As far as I am concerned, I am done with it.
I disagree	I disagree with the thought of buying a new car even when we already have two.
From my point of view	The sin is terrific from my point of view.

3.8. Explanatory Linkers in English Grammar

Explanatory sentence connectors	**Linkers example**
More or less	There will be more or less 30 guests.
In general	Old people, in general, like to spend time with their grandkids.
Especially	It’s tough to sleep, especially after the strong coffee we drank.
In particular	All women, in particular, have to be strong and determined.
Essentially	An electric kettle is useful essentially for the winter months.
Basically	The cake is basically full of chocolates.
In other words	The problem, In other words, is that we have to re-write the whole script.
In short	The outing, in short, could not lift up my mood.

Above all	The idea behind the meeting is, above all, to make the employees aware of the current financial crisis faced by the company.
At least	At least now when you know that we are here, you can jump in any day.

3.9. Comparison

English comparison connectors list	English connectors example
As …as	He is as good as his sister.
Equally	Both of them are equally talented.
As if	It seems as if they have cried a lot.
Similarly	We have chosen our group members, similarly, you can do that too.
Comparable	Today's weather is comparable with that of Darjeeling.
Like	He was determined to get a high-rank job like his cousin.
In like manner	All responded in a like manner.
In the same way	Now do the rest of the drawing in the same way as I did.
Despite this	She kept on going despite this injury on her left feet.
Alternatively	You can go to that Italian restaurant or alternatively you can even choose the Mexican food counter on the opposite side of the road.
By the way	By the way, here is my card.
Unless	I won't pay you unless you drop me to the right stoppage.

3.10. Emphasis Connector Words

English connectors list	Example
Also	He was told to study and also to take care of the dog.
Indeed	She was sweet indeed but needed proper grooming.
Of course	Sportsmen have a competitive approach while playing but of course, that should not be carried off the ground,
Certainly	Certainly, she has witnessed something cruel otherwise she would not be so nervous.
Specifically	He specifically looked for a diamond-studded ring.
Significantly	Her health was significantly improving.
Notably	Her academic career has been notably amazing.

3.11. Addition Linkers in English Grammar

Sentence connectors	Linker words example
As well as	The sound, as well as the picture quality, is amazing.

Further	I introduced him to the other members and that's it, I had no further conversation.
and then	John came from swimming and then left for basketball coaching.
And	He and other members went to the party.
Too	He too misbehaved with the maid.
In addition to	In addition to the notes, the teacher also suggested some reference books for the preparation.
Not only – but also	We are not only harming the environment but also becoming inhuman day by day.
Or	We can go to the movies or to the park.

3.12. Illustration Connectors in English Grammar

Connector words	Example
Such as	There are many famous railway stations in the state of West Bengal such as Howrah, Sealdah, Ghum etc.
In this case	In this case, emotion will matter more than logic.
For one thing	He dedicated his entire youth for one thing only.
Illustrated by	The entire story was illustrated by Mr Sameer in a very clear manner.

3.13. Clause Connectors

Clause connectors are connector words used for connecting or joining clauses to create a grammatical and logical sentence.

There are three groups under clause connectors:

- Subordinator/subordinating conjunction
- Coordinating conjunction
- Sentence connector

a). Subordinator/ Subordinating Conjunction

After

Before

Since

Until

When

While

Because

Since

To make a contrast

Even though

Though

Whereas

b). Coordinating Conjunction

And

But

Yet

Or

Nor

For

And so

c). Sentence Connector

Furthermore

In addition

Besides

Moreover

However

Nevertheless

Otherwise

Consequently

And therefore

4. Conclusion

Connectors play an important role in English grammar as these help in forming sentences logically. There are different kinds of complex sentence connectors or phrase connectors but each of those has different usage.

Hopefully, this section will help you in identifying the different connectors in English and will also make you understand the uses.

Chapter II

Reading, Comprehension and Resuming a Scientific Text

Text N° 1:

Materials Sciences

Matter, at the microscopic scale, is composed of particles. These particles are either atoms or molecules. The organization of these particles can be varied from complete disorder in gases at low pressure to perfect order in crystals. All human activity sectors are extremely dependent on materials, from the manufacture of electronic components to the construction of space shuttles. Materials play an important role in the development of human civilization. They are classified according to their composition and their properties. We distinguish three main classes of materials: Metals and their alloys, polymers and plastics, ceramics and glasses. This classification is based on the nature of chemical bonds and atomic structure. The fourth class of materials added to the three main classes, is the “composite materials”. These materials are obtained by combining two or more materials of the first three classes. A composite material exhibits particular properties, like metallic alloys, which are a combination of two or more metals.

- Metals and their alloys are good conductors of electric current and heat. They have a rigid and plastically deformable structure. Their melting temperatures are generally high.
- Polymers and plastics are organic materials. They constituted of molecules of very long chains of carbon atoms to which are attached groups of atoms comprising hydrogen, chlorine, sulfur, nitrogen, etc. Organic polymers are electrical and thermal insulators. They have a low density and are very easy to shape them. Their melting point is low, compared to that of metals.
- Ceramics are materials composed of metallic (Si, Al, Ti,..etc) and non-metallic elements, most often oxygen. Generally, ceramics are oxides (silica SiO_2, alumina Al_2O_3, etc.). Ceramics are refractory materials (high thermal resistance). They are generally very hard (abrasive) but brittle materials. This property limits their use in where the mechanical and thermal shocks are high. Most ceramics are electrical and thermal insulators.

<u>Questions:</u>

1. Read, carefully, the text and give an appropriate title.
2. List the different classes of materials.
3. Cite the factors responsible of this classification.
4. Identify the properties of each materials class.
5. Give a short description in three lines of each class of materials.
6. Summarize the text in 8 lines maximum.

Text N° 2:

Quantum mechanics

Quantum mechanics is the study of matter and its interactions with energy on the atomic and subatomic scales. By contrast, classical physics explains matter and energy only on a scale corresponding to human experience, including the behavior of astronomical bodies such as the moon, earth, sun….etc. Classical physics is still used in much of modern science and technology. However, towards the end of the 19^{th} century, scientists discovered phenomena in both the large (macro) and the small (micro) scles that classical physics could not explain. The desire to resolve inconsistencies between observed phenomena and classical theory leads to the development of quantum mechanics.

In quantum mechanics, particles have wavelike properties. Thus, they will be studied through a particular wave equation called "Schrodinger equation". Erwin Schrödinger introduced his first wave equation in the year 1926. He proposed the quantum mechanical model of the atom treating electrons as matter waves. Schrödinger's equation : $H\ \psi = E\ \psi$ is a linear partial differential equation that governs the wave function of a quantum-mechanical system. It mainly allows interpreting the wave function of a particle ψ related to its probability of presence at a certain place, in a certain quantum state. Note that, the Schrödinger equation is not the only way to study quantum mechanical systems and make predictions. Other formulations of quantum mechanics include matrix mechanics, introduced by Werner Heisenberg, and the path integral formulation, developed chiefly by Richard Feynman. When these approaches are compared, the use of the Schrödinger equation is sometimes called "wave mechanics".

Questions:

1. Give a short title to the corresponding text.
2. Give a concrete definition of quantum mechanics.
3. How are the particles are treated in quantum theory ?
4. Give a short comparison between classical physics and quantum physics.
5. What does the Schrödinger equation express ?
6. Is the Schrödinger equation the only one which can describe the quantum systems ?
   - If no, cite other formulations.
7. Give a short abstract of this scientific text.

Text N° 3

Growth of In_2O_3 on In metal and on InSb by the electron irradiation

Recently, the development of indium oxide such as In_2O_3 on the III–V semiconductors shows successful technological applications as in the gas sensor field, the emission devices, the biotechnology,…etc. The indium oxide In_2O_3 has attracted a great attention due to its various synthesis methods. In our study, we are interested in developing of indium oxide In_2O_3 on the In and InSb surfaces by electron beam stimulated oxidation. The formation of In_2O_3 on InSb was advantaged by a previous treatment due to the sputtering of the surface by the argon ions at low energy 300 eV with a current density of 2 $\mu A/cm^2$ followed by heating at 300°C in UHV. Our results have been tracked by Auger electron spectroscopy (AES) and Electron Energy Loss Spectroscopy (EELS) which are suited to study the surface with respect to physical structure and chemical composition.

Questions:

1. What do III-V semiconductors mean?
2. Why has In_2O_3 attracted considerable research?
3. How In_2O_3 is developed on In and InSb surfaces?
4. Why Auger electron spectroscopy (AES) and electron energy loss spectroscopy (EELS) were used?
5. Give a short abstract of this scientific text.

Text N° 4

Integrated circuits

An integrated circuit or monolithic integrated circuit (also referred to as an IC) is a set of electronic circuits on one small flat piece of semiconductor material, usually silicon. Large numbers of miniaturized transistors and other electronic components are integrated together on the flat piece. These results in circuits that are orders of magnitude smaller, faster, and less expensive than those are constructed of discrete components, allowing a large transistor count. The IC's mass production capability, reliability, and building-block approach to integrated circuit design has ensured the rapid adoption of standardized ICs in place of designs using discrete transistors. ICs are now used in virtually all electronic equipment and have revolutionized the world of electronics. Computers, mobile phones and other home appliances are now inextricable parts of the structure of modern societies, made possible by the small size and low cost of ICs such as modern computer processors and microcontrollers.

Very-large-scale integration was made practical by technological advancements in semiconductor device fabrication. Since their origins in the 1960s, the size, speed, and capacity of chips have progressed enormously, driven by technical advances that fit more and more transistors on chips of the same size.

<u>Questions:</u>

1. Read, carefully, the text and give an appropriate title.
2. Give a concrete definition of an integrated circuit.
3. The assembly of different electronic devices on one chip give to the integrated circuit different properties. Cite these properties.
4. List the different application areas of integrated circuit.
5. Explain how integrated circuit technology is based on the development of semiconductors fabrication methods.
6. Summarize the text in 8 lines maximum.

Text N° 5

Lasers

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The word laser is an acronym that originated from light amplification by stimulated emission of radiation. The first laser was built in 1960 by Theodore Maiman at Hughes Research Laboratories, based on theoretical work by Charles H. Townes and Arthur Leonard Schawlow.

A laser differs from other sources of light in that it emits a coherent light. This spatial coherence allows a laser to be focused to a tight spots. It also allows a laser beam to stay narrow over great distances (collimation). Lasers can also have high temporal coherence, which permits them to emit light with a very narrow frequency spectrum. Alternatively, temporal coherence can be used to produce ultrashort pulses of light with a broad spectrum but durations as short as a femtosecond.

Lasers are used in optical disc drives, laser printers, barcode scanners, DNA sequencing instruments, optic fibers, and free-space optical communication, semiconducting chip manufacturing (photolithography), laser surgery and skin treatments, cutting and welding materials, military and law enforcement devices for marking targets and measuring range and speed, and in laser lighting displays for entertainment.

Semiconductor lasers in the blue to near-UV have also been used in place of light-emitting diodes (LEDs) to excite fluorescence as a white light source. This permits a much smaller emitting area due to the much greater radiance of a laser and avoids the droop suffered by LEDs; such devices are already used in some car headlamps.

Questions:

1. Give the physical principle of lasers.

2. Who is the scientist who created the first laser and in what year ?

3. What are the characteristics of a laser light ?

4. Cite four application areas of lasers.

5. Give a short abstract of 250 words by introducing the following different connectors: Indeed, furthermore, in fact, however.

Text N° 6

Solar cell

A solar cell or photovoltaic cell (PV cell) is an electronic device that converts the energy of light directly into electricity by means of the photovoltaic effect. It is a form of photoelectric cell, a device whose electrical characteristics (such as current, voltage, or resistance) vary when exposed to light. Individual solar cell devices are often the electrical building blocks of photovoltaic modules, known colloquially as "solar panels". The common single-junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts. Photovoltaic cells may operate under sunlight or artificial light. In addition to producing energy, they can be used as a photodetector (for example infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity.

The operation of a PV cell requires three basic attributes:

- The absorption of light, generating excitons (bound electron-hole pairs), unbound electron-hole pairs (via excitons), or plasmons.
- The separation of charge carriers of opposite types.
- The separate extraction of those carriers to an external circuit.

In contrast, a solar thermal collector supplies heat by absorbing sunlight, for the purpose of either direct heating or indirect electrical power generation from heat. A "photoelectrolytic cell" (photoelectrochemical cell), on the other hand, refers either to a type of photovoltaic cell (like that developed by Edmond Becquerel and modern dye-sensitized solar cells), or to a device that splits water directly into hydrogen and oxygen using only solar illumination.

Photovoltaic cells and solar collectors are the two means of producing solar power.

Questions:

1. Give a concrete definition of solar cells.

2. Cite the difference between solar cells and solar panels.

3. Explain the main basic attributes to make a PV cell in operation.

4. What is the difference between a solar thermal collector and a photoelectrolytic cell ?

5. Give a short abstract of 300 words by introducing the following different connectors: in addition, whereas, however, indeed, furthermore, in fact.

Chapter III

English analysis of a Scientific Articles

Article N° 01

Invited paper

History of Semiconductors

Lidia Łukasiak and Andrzej Jakubowski

Abstract—The history of semiconductors is presented beginning with the first documented observation of a semiconductor effect (Faraday), through the development of the first devices (point-contact rectifiers and transistors, early field-effect transistors) and the theory of semiconductors up to the contemporary devices (SOI and multigate devices).

Keywords—band theory, laser, Moore's law, semiconductor, transistor.

1. Introduction

There is no doubt that semiconductors changed the world beyond anything that could have been imagined before them. Although people have probably always needed to communicate and process data, it is thanks to the semiconductors that these two important tasks have become easy and take up infinitely less time than, e.g., at the time of vacuum tubes.

The history of semiconductors is long and complicated. Obviously, one cannot expect it to fit one short paper. Given this limitation the authors concentrated on the facts they considered the most important and this choice is never fully impartial. Therefore, we apologize in advance to all those Readers who will find that some vital moments of the semiconductor history are missing in this paper.

The rest of this paper is organized in four sections devoted to early history of semiconductors, theory of their operation, the actual devices and a short summary.

2. Early History of Semiconductors

According to G. Busch [1] the term "semiconducting" was used for the first time by Alessandro Volta in 1782. The first documented observation of a semiconductor effect is that of Michael Faraday (1833), who noticed that the resistance of silver sulfide decreased with temperature, which was different than the dependence observed in metals [2]. An extensive quantitative analysis of the temperature dependence of the electrical conductivity of Ag_2S and Cu_2S was published in 1851 by Johann Hittorf [1].

For some years to come the history of semiconductors focused around two important properties, i.e., rectification of metal-semiconductor junction and sensitivity of semiconductors to light and is briefly described in Subsections 2.1 and 2.2.

2.1. Rectification

In 1874 Karl Ferdinand Braun observed conduction and rectification in metal sulfides probed with a metal point (whisker) [3]. Although Braun's discovery was not immediately appreciated, later it played a significant role in the development of the radio and detection of microwave radiation in WWII radar systems [4] (in 1909 Braun shared a Nobel Prize in physics with Marconi). In 1874 rectification was observed by Arthur Schuster in a circuit made of copper wires bound by screws [4]. Schuster noticed that the effect appeared only after the circuit was not used for some time. As soon as he cleaned the ends of the wires (that is removed copper oxide), the rectification was gone. In this way he discovered copper oxide as a new semiconductor [5]. In 1929 Walter Schottky experimentally confirmed the presence of a barrier in a metal-semiconductor junction [5].

2.2. Photoconductivity and Photovoltaics

In 1839 Alexander Edmund Becquerel (the father of a great scientist Henri Becquerel) discovered the photovoltaic effect at a junction between a semiconductor and an electrolyte [6]. The photoconductivity in solids was discovered by Willoughby Smith in 1873 during his work on submarine cable testing that required reliable resistors with high resistance [7]. Smith experimented with selenium resistors and observed that light caused a dramatic decrease of their resistance. Adams and Day were the first to discover the photovoltaic effect in a solid material (1876). They noticed that the presence of light could change the direction of the current flowing through the selenium connected to a battery [8]. The first working solar cell was constructed by Charles Fritts in 1883. It consisted of a metal plate and a thin layer of selenium covered with a very thin layer of gold [8]. The efficiency of this cell was below 1% [9].

3. Theory

In 1878 Edwin Herbert Hall discovered that charge carriers in solids are deflected in magnetic field (Hall effect). This phenomenon was later used to study the properties of semiconductors [10]. Shortly after the discovery of the electron by J. J. Thomson several scientists proposed theories of electron-based conduction in metals. The theory of Eduard Riecke (1899) is particularly interesting, because he assumed the presence of both negative and positive charge carriers with different concentrations and mobilities [1]. Around 1908 Karl Baedeker observed the dependence of the conductivity of copper iodide on the stoichiometry (iodine content). He also measured the Hall effect in this material, which indicated carriers with positive charge [1]. In 1914 Johan Koenigsberger divided solid-state materials into three groups with respected to their conductivity: metals, insulators and "variable conductors" [1]. In 1928 Ferdinand Bloch developed the theory of electrons in lattices [10]. In 1930 Bernhard Gudden reported that the observed properties of semiconductors were due exclusively to the presence of impurities and that chemically pure semiconductor did not exist [1].

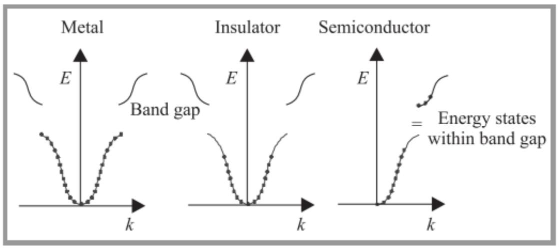

Fig. 1. Alan Wilson's theory of bands in solids.

In 1930 Rudolf Peierls presented the concept of forbidden gaps that was applied to realistic solids by Brillouin the same year. Also in 1930 Kronig and Penney developed a simple, analytical model of periodic potential. In 1931 Alan Wilson developed the band theory of solids based on the idea of empty and filled energy bands (Fig. 1). Wilson also confirmed that the conductivity of semiconductors was due to impurities [10]. In the same year Heisenberg developed the concept of hole (which was implicit in the works of Rudolf Peierls [10]). In 1938 Walter Schottky and Neville F. Mott (Nobel Prize in 1977) independently developed models of the potential barrier and current flow through a metal-semiconductor junction. A year later Schottky improved his model including the presence of space charge. In 1938 Boris Davydov presented a theory of a copper-oxide rectifier including the presence of a p-n junction in the oxide, excess carriers and recombination. He also understood the importance of surface states [11]. In 1942 Hans Bethe developed the theory of thermionic emission (Nobel Prize in 1967).

4. Devices

4.1. Point-Contact Rectifiers

In 1904 J. C. Bose obtained a patent for PbS point-contact rectifiers [12]. G. Pickard was the first to show that silicon point-contact rectifiers were useful in detection of radio waves (patent in 1906) [10]. The selenium and copper oxide rectifiers were developed, respectively, in 1925 by E. Presser and 1926 by L. O. Grondahl [10]. The selenium rectifiers were heavily used in the WWII in military communications and radar equipment [10].

4.2. The p-n Junction

During his work on the detection of radio waves Russel Ohl realized that the problems with cat's whisker detectors were caused by bad quality of the semiconductor. Therefore he melted the silicon in quartz tubes and then let it cool down. The obtained material was still polycrystalline but the electrical tests demonstrated that the properties were much more uniform. Ohl identified the impurities that created the p-n junction that he accidentally obtained during his technological experiments. He held four patents on silicon detectors and p-n junction [13].

4.3. Bipolar Transistor

In 1945 William Shockley put forward a concept of a semiconductor amplifier operating by means of the field-effect principle. The idea was that the application of a transverse electric field would change the conductance of a semiconductor layer. Unfortunately this effect was not observed experimentally. John Bardeen thought that this was due to surface states screening the bulk of the material from the field (Fig. 2). His surface-theory was published in 1947 [14].

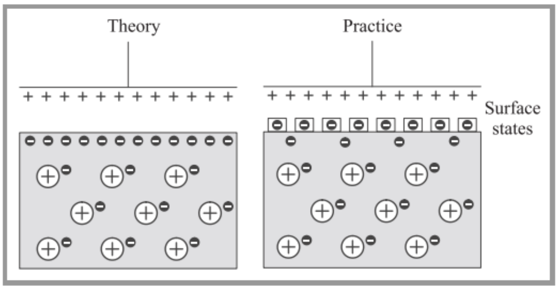

Fig. 2. The idea of surface states.

While working on the field-effect devices, in December 1947 John Bardeen and Walter Brattain built a germanium point-contact transistor (Fig. 3) and demonstrated that this device exhibited a power gain. There was, however, an uncertainty concerning the mechanism responsible for the transistor action [13]. Bardeen and Brattain were convinced that surface-related phenomena had the dominant role in the operation of the new device while Shockley favoured bulk conduction of minority carriers. About one month later he developed a theory of a p-n junction and a junction transistor [15]. Shockley, Bardeen and Brattain received the Nobel Prize in physics in 1956 (John Bardeen received another one in 1972 for his theory of superconductivity). In February 1948 John Shive demonstrated a correctly operating point-contact transistor with the emitter and collector placed on the opposite sides of a very thin slice of germanium (0.01 cm). This configuration indicated that the conduction was indeed taking place in the bulk, not along the surface (the distance between the emitter and collector along the surface would be much longer) [15]. It was only then that Shockley presented his theory of transistor operation to the coworkers [15], [16].
It is worth remembering that the crucial properties of semiconductors at the time were "structure sensitive"

(as Bardeen put it in [14]), that is they were strongly dependent on the purity of the sample. The semiconductor material with which Bardeen and Brattain worked was prepared using a technique developed by Gordon K. Teal and John B. Little based on the Czochralski method. The crystal was then purified using the zone refining method proposed by William G. Pfann [11].

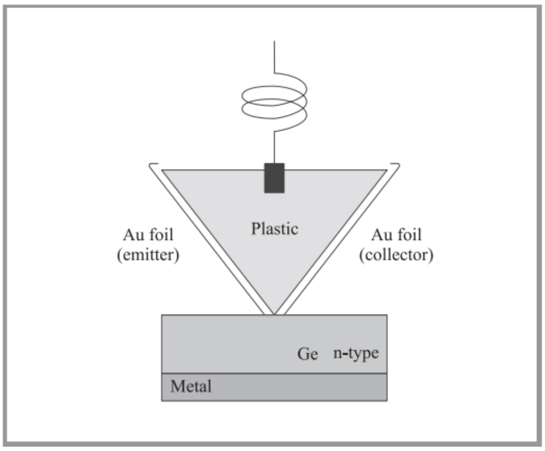

Fig. 3. The first point-contact transistor [16].

Point-contact transistors were the first to be produced, but they were extremely unstable and the electrical characteristics were hard to control. The first grown junction transistors were manufactured in 1952. They were much better when compared to their point-contact predecessor, but the production was much more difficult. As a result of a complicated doping procedure the grown crystal consisted of three regions forming an n-p-n structure. It had to be cut into individual devices and contacts had to be made. The process was difficult and could not be automated easily. Moreover, a lot of semiconductor material was wasted. In 1952 alloyed junction transistor was reported (two pellets of indium were alloyed on the opposite sides of a slice of silicon). Its production was simpler and less material-consuming and could be automated at least partially. The obtained base width was around 10 μm, which let the device operate up to a few MHz only. The first diffused Ge transistor (diffusion was used to form the base region, while the emitter was alloyed) with a characteristic "mesa" shape was reported in 1954. The base width was 1 μm and the cut-off frequency 500 MHz. It was generally understood that for most applications silicon transistors would be better than germanium ones due to lower reverse currents. The first commercially available silicon devices (grown junction) were manufactured in 1954 by Gordon Teal. The first diffused Si transistor appeared in 1955. To reduce the resistivity of the collector that limited the operation speed without lowering the breakdown voltage too much John Early thought of a collector consisting of two layers, i.e., high-resistivity one on top of a highly doped one. A transistor with epitaxial layer added was reported in 1960. In the same year Jean Hoerni proposed the planar transistor (both base and emitter regions diffused). The oxide that served as a mask was not removed and acted as a passivating layer [15].

Further improvement of speed was proposed by Herbert Kroemer. A built-in electric field could be introduced into the base by means of graded doping. Another way of introducing the electric field in the base he thought of was grading the composition of the semiconductor material itself, which resulted in graded band gap. This heterostructure concept could not be put to practice easily because of fabrication problems [17].

4.4. Integrated Circuit

The transistor was much more reliable, worked faster and generated less heat when compared to the vacuum tubes [18]. Thus it was anticipated that large systems could be built using these devices. The distance between them had, however, to be as short as possible to minimize delays caused by interconnects. In 1958 Jack Kilby demonstrated the first integrated circuit where several devices were fabricated in one silicon substrate and connected by means of wire bonding. Kilby realized that this would be a disadvantage therefore in his patent he proposed formation of interconnects by means of deposition of aluminum on a layer of SiO_2 covering the semiconductor material [15]. This has been achieved independently by Robert Noyce in 1959. In 2000 Jack Kilby received a Noble Prize in physics for his achievements.

4.5. Tunnel Diode

Leo Esaki studied heavily doped junctions to find out how high the base of a bipolar transistor could be doped before the injection at the emitter junction became inadequate. He was aware that in very narrow junctions tunneling could take place. He obtained the first Ge tunneling diode in 1957 and a silicon one in 1958. Esaki's presentation at the *International Conference of Solid State Physics in Electrons and Telecommunications* in 1958 was highly appreciated by Shockley [19]. Unfortunately, Shockley exhibited a complete lack of interest when Robert Noyce came to him to present his idea of a tunnel diode two years earlier. As a result Noyce moved to other projects [20]. The tunnel diode was extremely resistant to the environmental conditions due to the fact that conduction was not based on minority carriers or thermal effects. Moreover, its switching times were much shorter than those of the transistor. Leo Esaki received a Nobel Prize in physics in 1973 for his work on tunneling and superlattices [21], [22].

4.6. Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

In 1930 and 1933 Julius Lilienfeld obtained patents for devices resembling today's MESFET and MOSFET, respectively. In 1934 Oskar Heil applied for a patent for his theoretical work on capacitive control in field-effect transistors [3].

The first bipolar transistors were quite unreliable because semiconductor surface was not properly passivated. A group directed by M. M. Atalla worked on this problem and found out that a layer of silicon dioxide could be the answer [23]. During the course of this work a new concept of a field-effect transistor was developed and the actual device manufactured [24]. Unfortunately, the device could not match the performance of bipolar transistors at the time and was largely forgotten [15]. Several years before Bell Laboratories demonstrated an MOS transistor Paul Weimer and Torkel Wallmark of RCA did work on such devices. Weimer made transistors of cadmium sulfide and cadmium selenide [11]. In 1963 Steven Hofstein and Fredric Heiman published a paper on a silicon MOSFET [25] (Fig. 4). In the same year the first CMOS circuit was proposed by Frank Wanlass [26]. In 1970 Willard Boyle and George Smith presented the concept of charge-coupled devices (CCD) – a semiconductor equivalent of magnetic bubbles [27]. Both scientists received a Nobel Prize in physics in 2009 for their work on CCD.

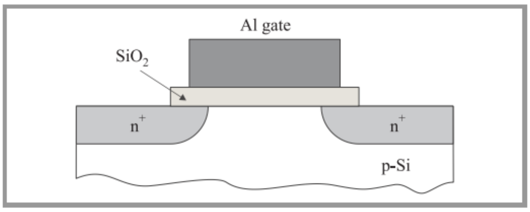

Fig. 4. A cross section of a metal-oxide-semiconductor transistor.

Early MOSFETs had aluminum gate. Development of a poly-Si gate [28] led to a self-aligned device, where the gate itself constitutes the mask for source and drain diffusion. In this way parasitic gate-to-source and gate-to-drain capacitances associated with gate overlap could be controlled. Since polysilicon had relatively high resistance, gates made of silicides of refractory metals were proposed (e.g., [29], [30]).

Reduction of the size of the device led to the so-called short-channel effects (SCE) including threshold voltage roll-off and drain-induced barrier lowering. The ways to cope with this problem include a reduction of the depth of source and drain [31] combined with efforts to avoid increased resistance (e.g., lightly doped drain [32], elevated source/drain (S/D) [33] or possibly Schottky barrier S/D [34]). Threshold voltage and punchthrough are controlled by means of the appropriate doping profile of the channel that makes it possible to maintain relatively good surface mobility (e.g., [35]). Short-channel effects are considerably reduced when gate oxide is thin. As a result of decreased thickness, gate leakage current obviously grows, increasing power consumption of the entire chip, which is an undesirable effect for battery-powered mobile systems. It is estimated that gate leakage current increases approximately 30 times every technology generation, as opposed to 3–5 times increase of channel leakage current [36]. Apart from leakage current, the reduction of gate-oxide thickness increases the susceptibility of the device to boron penetration from the poly-Si gate into the channel. A number of different high-*k* materials are extensively investigated.

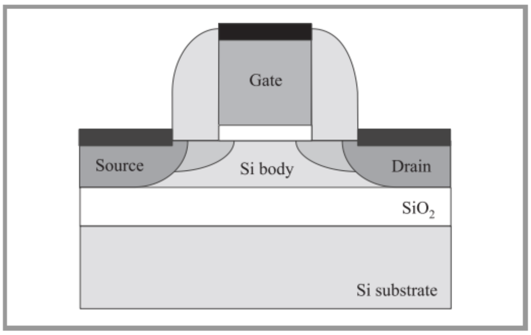

Fig. 5. A cross section of a SOI MOSFET.

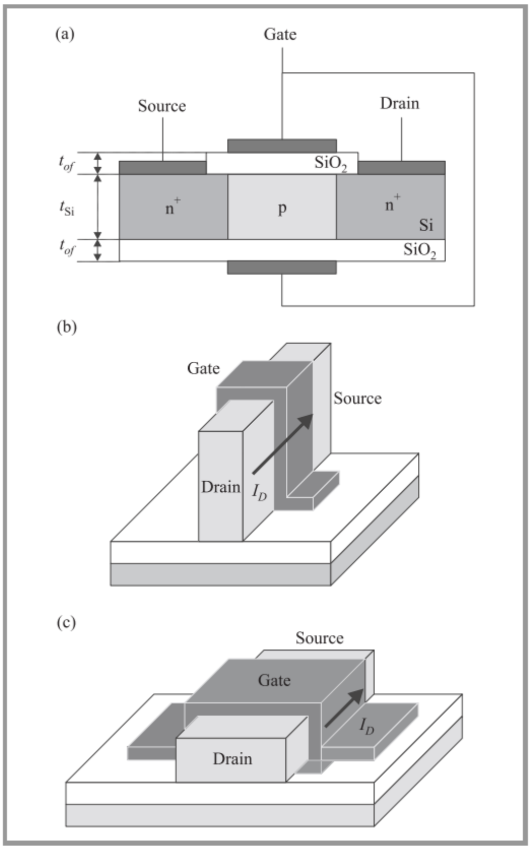

Fig. 6. Mutigate transistors: (a) double gate; (b) FinFET; (c) surrounding gate.

An interesting extension of the classical bulk MOSFET is silicon-on-insulator (SOI) – see Fig. 5 [37]. The advantage of SOI is the ease of electrical isolation of a device from the rest of the integrated circuit, which increases packing density. Moreover, the area of source and drain junctions is significantly reduced, thus decreasing parasitic capacitances. Finally, the depletion width is limited by the Si body thickness, therefore it is widely believed that SOI helps reduce short channel effects unless source-to-drain coupling through channel and BOX cannot be neglected. The properties of SOI devices are improved with the reduction of body thickness. It is believed that fully depleted ultra-thin-body SOI (FD UTB SOI) is one of the best scaling solutions. Due to excellent gate control of the channel these devices may be undoped or very lightly doped. In this way mobility is not degraded and threshold voltage is less dependent on the fluctuations of doping concentration [38]. Another advantage of SOI is that it facilitates development of new device concepts [39] (Fig. 6), but this is another story.

4.7. Semiconductor Lasers

Semiconductors are widely used for emission and detection of radiation. The first report on light emitted by a semiconductor appeared in 1907 in a note by H. J. Round. Fundamental work in this area was conducted, among other, by Losev. A very interesting description of the development of light-emitting diodes may be found in [40] while the history of photovoltaics is discussed in [8]. In this section only semiconductor lasers are mentioned briefly.

The first semiconductor lasers were developed around 1962 by four American research teams [41]. Further research in this area went in two directions, i.e., wider spectrum of materials to obtain wider wavelength range and concepts of new device structures. Herbert Kroemer and Zhores Alferov have independently come up with the idea that semiconductor lasers should be built on heterostructures. Zhores Alferov was a member of the team that created the first Soviet p-n junction transistor in 1953. He was directly involved in research aimed at development of specialized semiconductor devices for Russian nuclear submarines. The matter was of such importance for the Soviet authorities that he used to receive phone calls from very high government officials who wanted the work done faster. To fulfill those requests Alferov had to move to the lab and literally live there [42]. Later he worked on power devices and became familiar with p-i-n and p-n-n structures. When the first report on semiconductor lasers appeared, he realized that double heterostructures of the p-i-n type should be used in these devices [41]. He obtained the first practical heterostructure devices and the first heterostructure laser [42]. In 2000 Alferov and Kroemer (mentioned in Subsection 4.4) received a Nobel Prize in physics for their achievements in the area of semiconductor heterostructures used in high-speed- and optoelectronics.

Significant progress in semiconductor lasers is associated, among other, with the use of quantum wells and new materials, especially gallium nitride.

5. Summary

Silicon may be considered as the information carrier of our times. In the history of information there were two revolutions (approximately 500 years apart). The first was that of Johan Gutenberg who made information available to many, the other is the invention of the transistor. Currently the global amount of information doubles every year. Many things we are taking for granted (such as, e.g., computers, Internet and mobile phones) would not be possible without silicon microelectronics. Electronic circuits are also present in cars, home appliances, machinery, etc. Optoelectronic devices are equally important in everyday life, e.g., fiber-optic communications for data transfer, data storage (CD and DVD recorders), digital cameras, etc.

Since the beginning of semiconductor electronics the number of transistors in an integrated circuit has been increasing exponentially with time. This trend had been first noticed by Gordon Moore [43] and is called Moore's law. This law is illustrated in Fig. 7, where the number of transistors in successive Intel processors is plotted as a function of time (data after [44]).

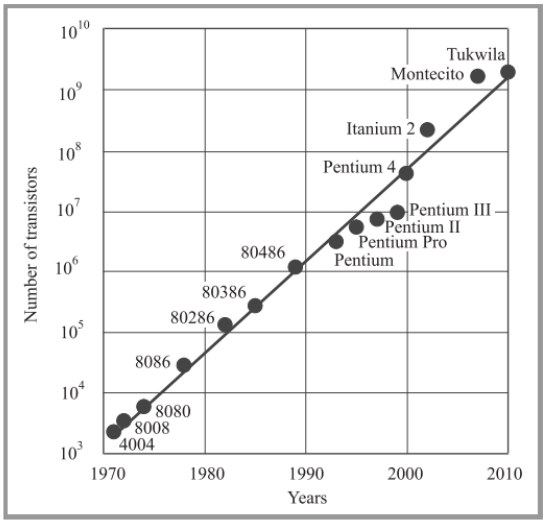

Fig. 7. Number of transistors in successive Intel processors as a function of time (data after [44]).

Even though the bipolar technology was largely replaced by CMOS (more than 90 percent of integrated circuits are manufactured in CMOS technology), Moore's law is still true in many aspects of the development trends of silicon microelectronics (obviously, with the appropriate time constant). The MOS transistor has been improved countless times but above everything else it has been miniaturized

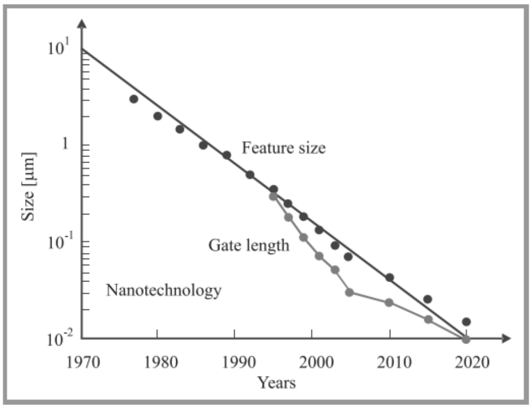

Fig. 8. Feature size as a function of time (data after [45]).

beyond imagination. The reduction of the feature size, presented in Fig. 8, is more or less exponential. The number of transistors produced per year and the average price are shown as a function of time in Fig. 9 (again the change is exponential). It is being anticipated that in 2010 approximately one billion transistors will be produced for every person living on the Earth.

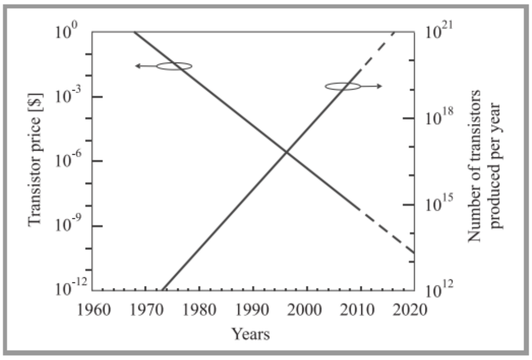

Fig. 9. Number of transistors produced per year and transistor price as a function of time (data after [46]).

We are pretty sure the future still holds a few surprises. Extensive research is being carried out on graphene, organic electronics, quantum devices, microsystems, integration of silicon with other materials and many other issues, but that is another story…

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Article N° 02

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BRIEF COMMUNICATION

Investigating the properties of tin-oxide thin film developed by sputtering process for perovskite solar cells

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Abstract

Tin oxide (SnO_2) nano-crystalline thin films were deposited on silicon and glass substrates at room temperature by sputtering at a constant power of 30 W and different working pressure of 10, 7, and 5 mTorr. Surface morphology, electrical and optical properties of the films were investigated to optimise the deposition condition of the films as electron transport layer (ETL) for high-power conversion efficiency perovskite solar cells. The films were characterized by scanning electron microscopy (SEM), UV–Vis–NIR Spectrophotometer, and Four-point probe. SnO_2 films obtained at working pressure of 10 mTorr exhibited uniform surface morphology with high light transmittance (90%) and conductivity (4 S/m). These sputtered SnO_2 films appeared to have shown promising properties as ETL for PSC, and further investigation is justified to establish the optimal fabrication parameters and resulting energy conversion efficiency.

Keywords Sputtering · Tin oxide · Electron transport layer · Thin films · SEM · Perovskite solar cells

Introduction

Renewable energy sources, such as wind, hydro, solar, hydrogen, and bio, are free of pollution and afford great relief from the global warming threat posed by the excessive burning of fossil fuels (e.g., coal, oil, and gas). Solar energy is the most abundant of all energy resources for heat, light, and electricity generation through thermal power generators and solar cells [1, 2]. A solar cell converts solar radiation into electric power by a chemical or physical process called the photovoltaic (PV) effect. This technology is clean and green, and produces no greenhouse effect on the environment [3, 4]. Despite all these benefits, because of high manufacturing and installation cost, the usage of solar technology for power generation is only 1% [5].

The emergence of second-generation thin-film solar cells with less material and reduced weight of the PV cells developed using innovative manufacturing technologies, and the possible fabrication of tandem cells with reasonably high-power conversion efficiency (PCE) make them attractive in critical applications [6]. The third-generation solar cells are based on semiconducting organic, inorganic, or hybrids including one of the highly promising perovskite solar cells (PSCs). The operation of the PSCs under direct solar energy involves electron and hole generation by light absorption of the perovskite material, charge separation into opposite sides, and collection of charge to the output circuit. The perovskite solar cell involves an organic absorber of perovskite structure, a p-type hole transport layer (HTL), and an n-type electron transport layer (ETL) of metal-oxide thin film [7]. The PSC consists of regular or inverted architecture as seen in Fig. 1. The perovskite structure is stable and can significantly contribute to the effectiveness of the solar cell arrangement as an organic absorber.

The NREL-certified record efficiency of PSC is 25.7% [8], and further improvement can be achieved with a better understanding of device architectures and resulting PCE due to optimal processing conditions. Moreover, the manufacturing process of these cells is simpler and more

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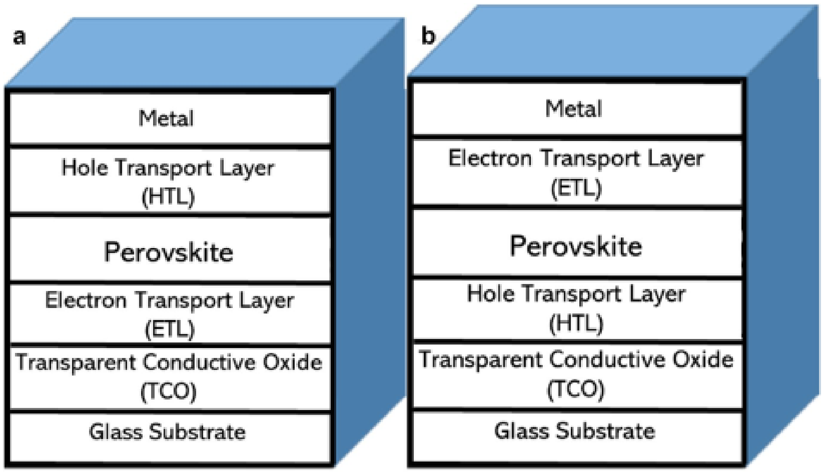

Fig. 1 Perovskite solar cell: **a** n–i–p planer regular architecture and **b** p–i–n inverted planer architecture

economical than that of the second- and third-generation solar cells [6, 9, 10]. The ETL and HTL play a vital part in achieving highly efficient devices with sustainability. However, regarding efficiency, ETLs suitable energy-level alignment improves charge separation and decrease recombination which produces better short-circuit current and higher fill factor [11]. The role of ETL is critical as they facilitate the photo-electron flow to the external circuit and deter short-circuiting by stopping the passage of the holes produced in the perovskite to the conductive electrode [9]. The ETL should be compact enough with excellent charge collection ability, pinhole-free, with a fitting bandgap and energy level, and good transparency [9]. The optimization of an n-type compact layer based on its ETL is critical to the efficiency enhancement of the PSC as it is responsible for electron conductivity/transport [7]. Still aiming to enhance the ETL, most research in recent years focused on investigating the consequence of ETL thickness and its feasible advancement strategy [12]. High resistance means thick ETL that opposes electron flow resulting in low PCE as the electrons have to travel longer distance to reach the top electrode. This was demonstrated by Jeyakumar et al. with titanium Oxide (TiO_2) ETL [13]. The cell series resistance will be very high if the ETL is too thick; subsequently, *Jsc* and Fill Factor of the cell reduce. Similarly, very-thin ETL thickness will encourage direct contact amid transparent conductive oxide (TCO) and perovskite resulting in carrier recombination and low hole-blocking efficiency. TiO_2 films, prepared by spray pyrolysis, were observed to have pinholes in ETL that resulted in the poor PCE of the PSCs [14]. The atomic layer deposition (ALD) technique provided a conformal, homogenous, and compact ETL with mesoscopic structure, having porous metal-oxide support on the films, and fewer pin holes that upsurged the PCE of the PSC from 4 to 13.6% [15]. However, despite the advantage of the mesoscopic structure, the TiO_2 requires a high temperature (more than 450 °C) to process, which makes the operation hazardous and cost-intensive [16]. The last record (2022) of PSC has been found using SnO_2 quantum dot as ETL could be more efficient with a better-aligned conduction band (see Fig. 2b), higher carrier mobility, and high operational stability [17]. This is attributed more to its barrier-free active conformation, and thus, ions are not restricted from reaching the perovskite. Thus, tin oxide (SnO_2) with better optical and electrical features that can be processed a low temperature could be a better alternative to TiO_2 thin film as ETL in PSCs [16], as shown in Fig. 2a. In terms of stability of PSC device, SnO_2 as ETL is higher than TiO_2 and ZnO due to wide bandgap (see Fig. 2c and d) with absorbing fewer UV [9, 18].

SnO_2 is an amphoteric compound of an inorganic composition having a cassiterite mineral form and exhibits good optical and electrical properties [19]. It is also mechanically hard, atmospherically stable, chemically inert, and high-temperature resistant [20]. Various studies revealed that monocrystalline film of SnO_2 is more than 18% hysteresis-free in PSC device [21]. Under forward and reverse voltage measurements, the PSCs with SnO_2 ETL on best performance attained 14.82% and 17.21% PCE, respectively [22, 23]. The fabrication of SnO_2 as an ETL for PSC produces an average PCE of 19.2–20.23% with mitigated hysteresis [21]. Jiang et al. [16] confirmed that introducing SnO_2 instead of fullerene or TiO_2 as an ETL in PSCs will mitigate interface charge accumulations and improve the transmission of charge generated in the perovskite absorber to the ETL due to its high electron mobility and conduction band as earlier reported by Correa and Baena et al. [18]. SnO_2 observes adequate energy-level alignment with the perovskite, exhibits

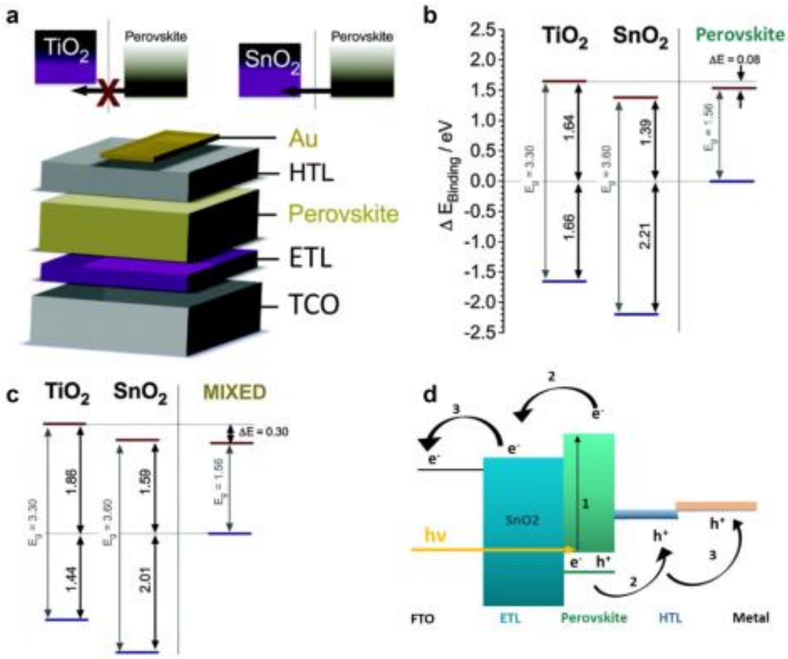

Fig. 2 **a** TiO_2 and SnO_2 energy levels, **b** electron injection potentials, **c** band-gap position of SnO_2, and **d** band-gap position [17, 18]

a wide bandgap of 3.6–4.0 eV [18] and an initial low resistivity and high conductivity (electron mobility) due to the presence of oxygen valences that produces carriers, and initiates a 15–150 meV donor platform/level [24]. SnO_2 as ETL induces low current loss as it absorbs light with higher energies than the bandgap [25]. SnO_2 films possess good transparency with ultimate absorption which corresponds to electron excitation from the valence band to the conduction band that determines the nature and value of the optical bandgap. Therefore, to ensure good passage of light through the ETL the film thickness of the ETL should be optimised to the best transparent quality alongside the reflectivity.

In general, this paper chose SnO_2 for its low cost, better band-gap energy alignment with perovskite, and good electrical and optical properties to enhance the PCE of the PSCs. In addition, SnO_2 is a promising material due to its low-temperature processing [26] in comparison to TiO_2 [16]. This research study examined properties of SnO_2 films deposited at different sputter pressure and room temperate by magnetron sputtering (see Fig. 3) for optimisation of the perovskite solar cell. Sputtering process allows

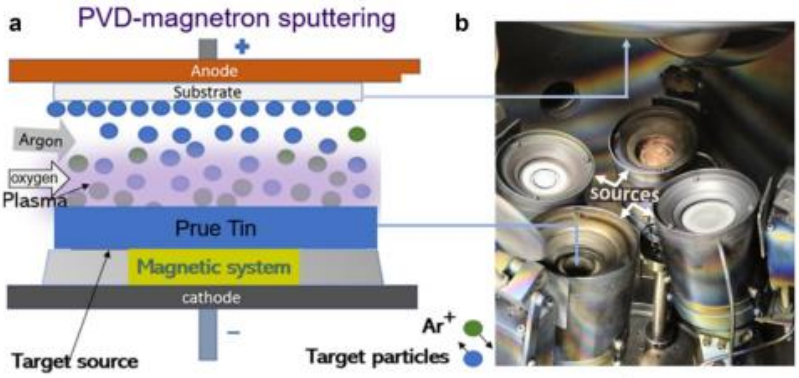

Fig. 3 **a** Magnetron sputtering process and **b** the internal view of the chamber

a controlled rate of film deposition, exceptional high film adhesion on substrates, outstanding film homogeneity on a large area, and good step coverage.

SnO_2 thin-film preparation

Sputtering is a physical vapour deposition technique that involves high energy (> 100 eV) ions (usually inert gas such as argon) to erode atoms on the surface of a target material. The ejected atoms must move freely toward the substrate. Sputtering occurs in vacuum to sustain high ion energies (plasma) and deter excess collisions of atom gas [27]. During the process, the gas atoms travel a mean free path (MFP) without any collision. The MFP fluctuates with pressure and is critical to unconstrained movement in the gas.

Magnetron sputtering involves a plasma discharge, confined, and sustained by a powerful field of magnet and secondary electrons to the area near the target plate. KJL PVD 75 is a conventional planar DC magnetron-sputtering machine that was used to prepare SnO_2 thin films onto glass and silicon substrates at different sputtering pressures and constant power deposition time and temperature. It has a cryogenic pump, reactive gas control system, and four HV magnetron-sputtering sources with RF DC and pulsed-DC power supplies. A circular flat disc of pure tin (99.9%) was used as the target material with a mixture of argon and oxygen as the working gas. The chamber was evacuated by the cryogenic pump with the sputter pressure monitored continuously using a Pirani and Penning pressure gauge. Three depositions were observed as the parameters are presented in Table 1.

Table 1 Parameters used in magnetron-sputtering process for SnO_2 thin-film fabrication

Common parameters			
Target material		Pure tin	
Target power (Watt)		30	
Deposition time (min)		60	
Ar/O_2 ratio		80:20	
Gas flowrate (cm^3/s)		11.5/2.3	
Substrate spin (rpm)		10	
Substrate Temp (°C)		25	
Variable parameters	Sample one (S1)	Sample two (S2)	Sample three (S3)
Base pressure (mTorr)	1.0×10^{-7}	1.0×10^{-7}	3.0×10^{-7}
Substrate	Glass and silicon	Glass	Glass
Working pressure (mTorr)	10	7	5

Characterization

The fabricated SnO_2 thin film was examined and analysed for transmittance and reflectance using a UV–Vis spectrophotometer, surface morphology using scanning electron microscopy (SEM), and electrical resistance and conductivity using a KeithLink four-point probe having constant probe diameter of 81 µm and probe spacing of 1.6 µm. The obtained results were compared with an optimal model for the application of PSC by Ref. [8].

Surface morphology

The surface morphology of the SnO_2 thin films on the silicon wafer and glass substrate was studied by observing SEM images captured using the TESCAN MIRA3 microscope. Figure 4 shows the surface feature of SnO_2 film deposited on silicon and glass substrates at working pressure of 10 mTorr. Apparently, at lower magnification, the surface looks quite smooth (see Fig. 4a and b), though a closer look at higher magnification shows vivid cracks that scatter incident light, thus decreasing light transmittance. On the other hand, instead of cracks, SnO_2 film deposited on glass substrate (see Fig. 4c and d) at 10 mTorr working pressure suffers from burnt grains like solid blisters that are irregular in size and distribution and is attributed to high scanning beam intensity from Tescan Mira. The morphology of the SnO_2 thin film on the glass substrates was further studied by depositing the SnO_2 at lower working pressure: 5 and 7 mTorr. The grains on the surface are smaller and more uniformly distributed films were created, as shown in Fig. 4g and h.

Film thickness and roughness

Film thickness and surface roughness were measured using stylus profilometer and atomic force microscopy (AFM), respectively, as shown in Table 2. The film thickness significantly decreases, whereas the surface roughness of the films slightly increases with increasing the working pressure from 5 to 10 mTorr. There is an optimum film thickness of ETL for high PCE perovskite solar cells, whereas the higher the surface roughness of the film, the higher the scattering loss of the incident light resulting in lower light transmittance. Therefore, there is a trade-off between the film thickness and the surface roughness of the SnO_2 film for optimum performance of PSCs.

Electrical properties

The electrical conductivity and resistance of the deposited SnO_2 films deposited at 10 and 7 mTorr (4 S/m) was found to be slightly higher than the film deposited at 5 mTorr (3

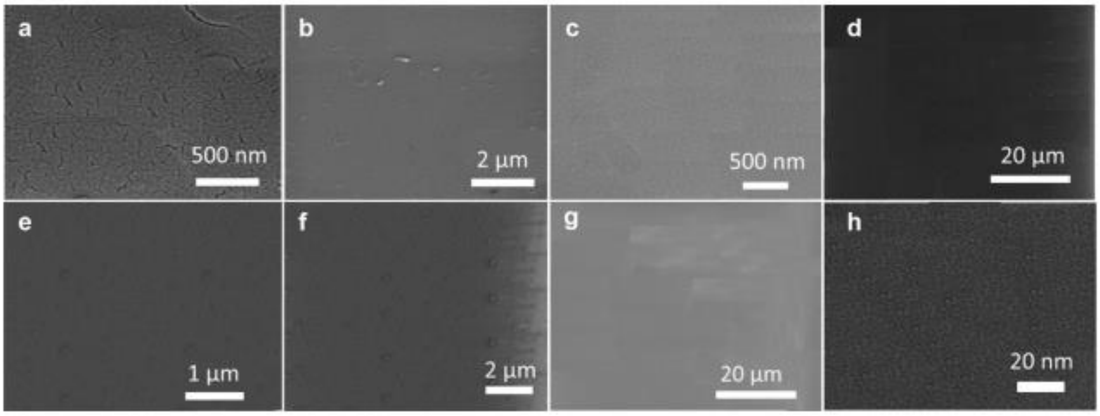

Fig. 4 SEM high and low magnification images of SnO_2 film deposited on silicon substrate (**a** and **b**) at 10 mTorr, and glass substrate (**c**, **d**), (**g**, **h**), and (**e**, **f**) at 10 and 7 and 5 mTorr working pressure, respectively

Table 2 Measured average film thickness, average surface roughness (Ra), and electrical conductivity (σ) at different sputter pressure (5, 7, 10 mTorr)

Samples	Pressure (mTorr)	Substrate	Thickness (nm)	Ra (nm)	σ (S/m)
S1	10	Silicon	58	2.00	–
		Glass	60	2.00	4
S2	7	Glass	72	1.85	4
S3	5	Glass	99	1.56	3

S/m) (see Table 2). The surface resistance and average resistance of the films at the different pressures (5, 7, 10 mTorr) are presented in Fig. 5a. The absolute values of the resistance were quite constant with insignificant variation against the different sputter pressure. Thus, working pressure is not a precursor parameter to affect resistivity.

Optical properties

The transmittance and reflectance spectra of the deposited SnO_2 films on the glass substrate were measured using dual beam CARY 500 UV–Vis–NIR in the solar wavelength spectrum (300 nm and 2500 nm), as shown in Fig. 5b. Only S1 maintained a close range of 90% transmittance and low reflectance, but the transmittance of the remaining two samples (S2 and S3) is much lower than this value (see Fig. 5b). From literature, common thickness used for ETL in PSCs was about 60 nm [28] and this value coincides with the SnO_2 film thickness of S1 (60 nm) with high transmittance that is useful for enhancing the PCE of the PCSs [18].

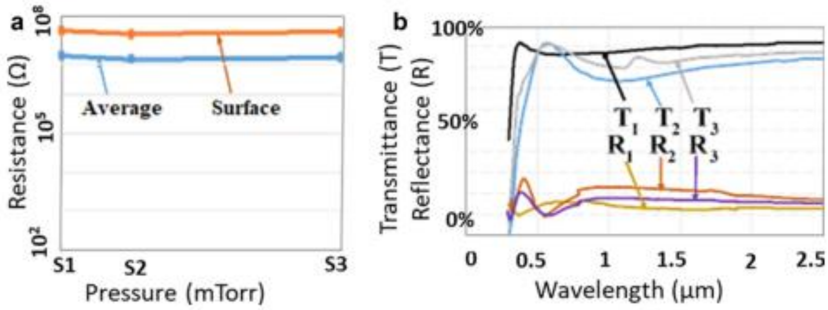

Fig. 5 **a** Average and surface electrical resistance at different pressure (10, 7, 5 mTorr for the individual samples), and **b** transmittance (T) and reflectance (R) of the films at different wavelength

Summary

From the focus on the ETL, SnO_2 thin films were fabricated on silicon and glass substrates for perovskite solar cells (PSCs) by magnetron sputtering at working pressure of 5, 7, and 10 mTorr and constant power of 30 W. The results could be summarised as follows:

- SEM images show cracks on the film produced on a silicon wafer at 10 mTorr, and hence, further investigation at 7 and 5 mTorr working pressure was discarded. On the other hand, small dots or grains could be seen on films produced on glass substrate.
- The variation in the electrical resistance and conductivity (varied between 3 and 4 S/m) of the films sputtered at different pressure (10, 7, 5 mTorr) was found insignificant.
- The transmittance of the SnO_2 film sputtered at 10 mTorr was found to be much higher (nearly 90%), than that the films deposited at 5 mTorr (75%) and 7 mTorr (82%).

The optimization of the electrical and optical properties, and the surface morphology of the SnO_2 film are dependent on deposition parameters, such as power, pressure, and temperature. The current study strongly demonstrates the potential application of SnO_2 thin film deposited at 10 mTorr and 30 W power with thickness of 60 nm for PSCs to achieve higher light conversion efficiency. Thus, further investigation is recommended to establish the optimal fabrication parameters and resulting electrical and optical properties including homogeneity and quality of the films.

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Data availability The data that support the findings of this study are available from the first and corresponding author, Chijioke Raphael Onyeagba, upon reasonable request.

Declarations

Conflict of interest The authors declare no known competing financial interests or personal relationships that could influence the work reported in this article.

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