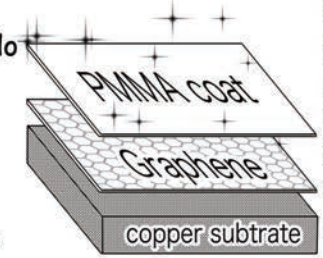
Chapter Three:
The Unprecedent Nature of Terahertz-Waves

But normally we'd do a proper coating on the completed graphene, and melt the copper substrate with etchant.



We used a basic recipe this time, which is why you'd have to scoop it up with the silicon substrate on a spatula.

令和3(2021)年度学術変革領域研究(A)
2.5D Materials
2.5次元物質科学：
社会変革に向けた物質科学のパラダイムシフト
NEWS LETTER

Welcome to the 2.5 D Laboratory

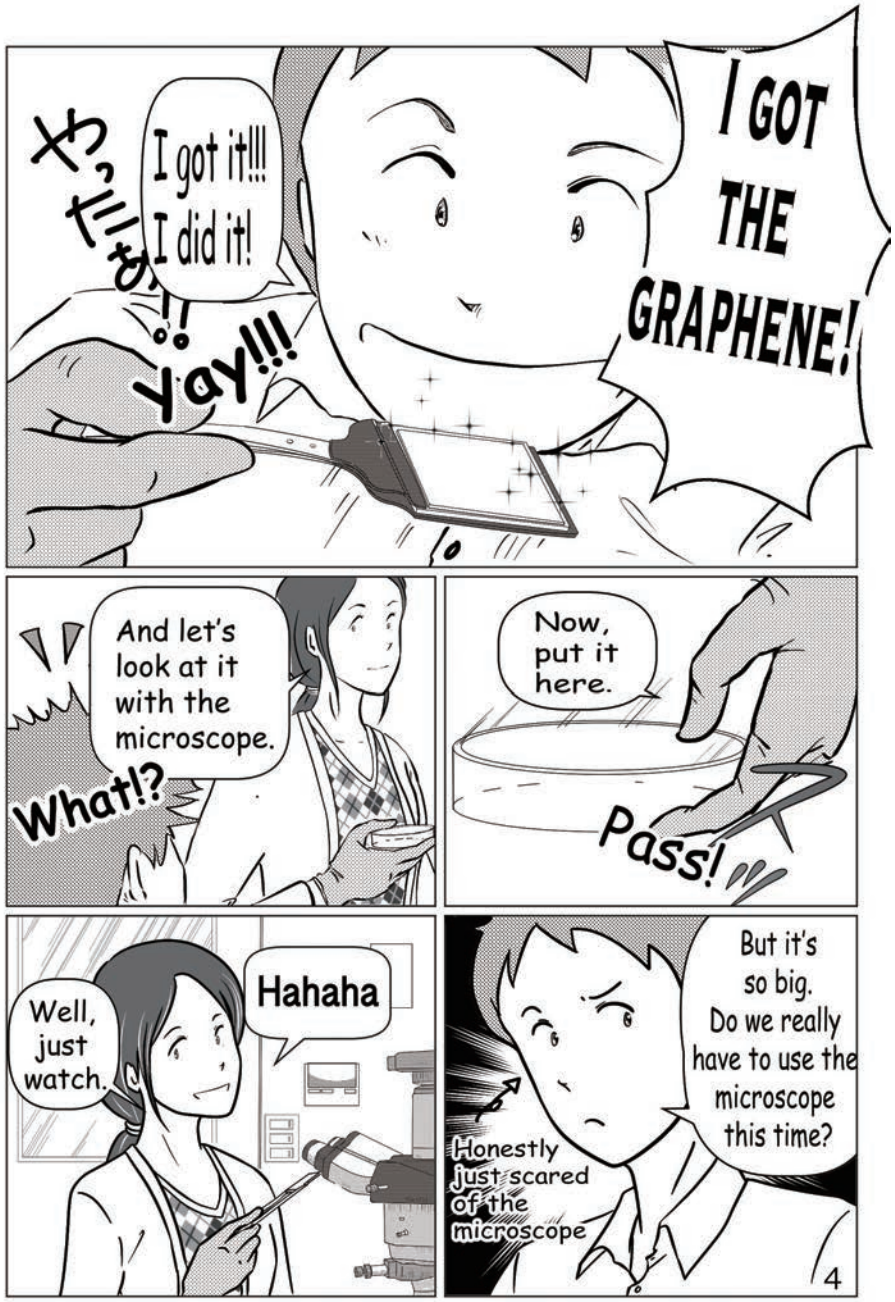
Previously in the series

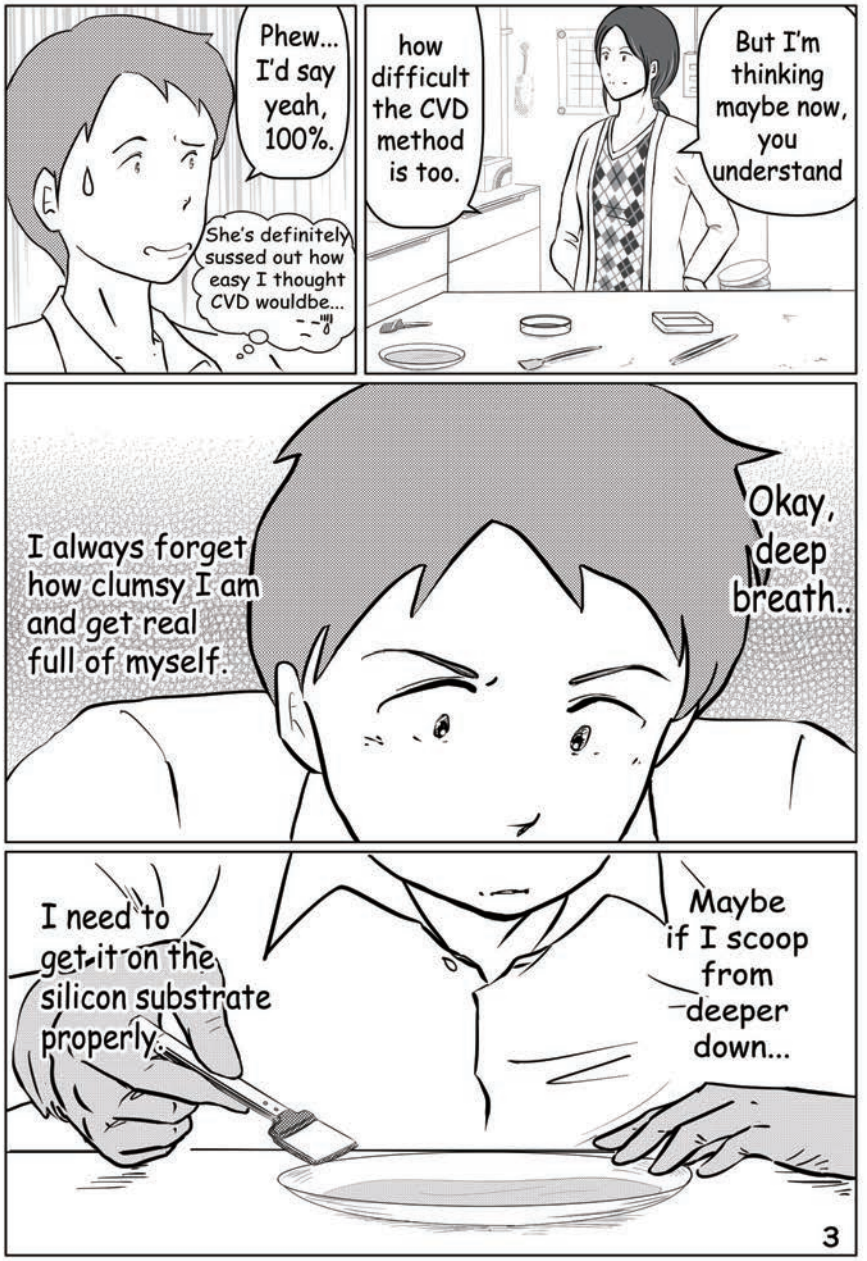
Koji Ota, a senior at university, takes on a graphene production entrance test to get into a cutting-edge science lab, but fails to get the results he needed with exfoliation.

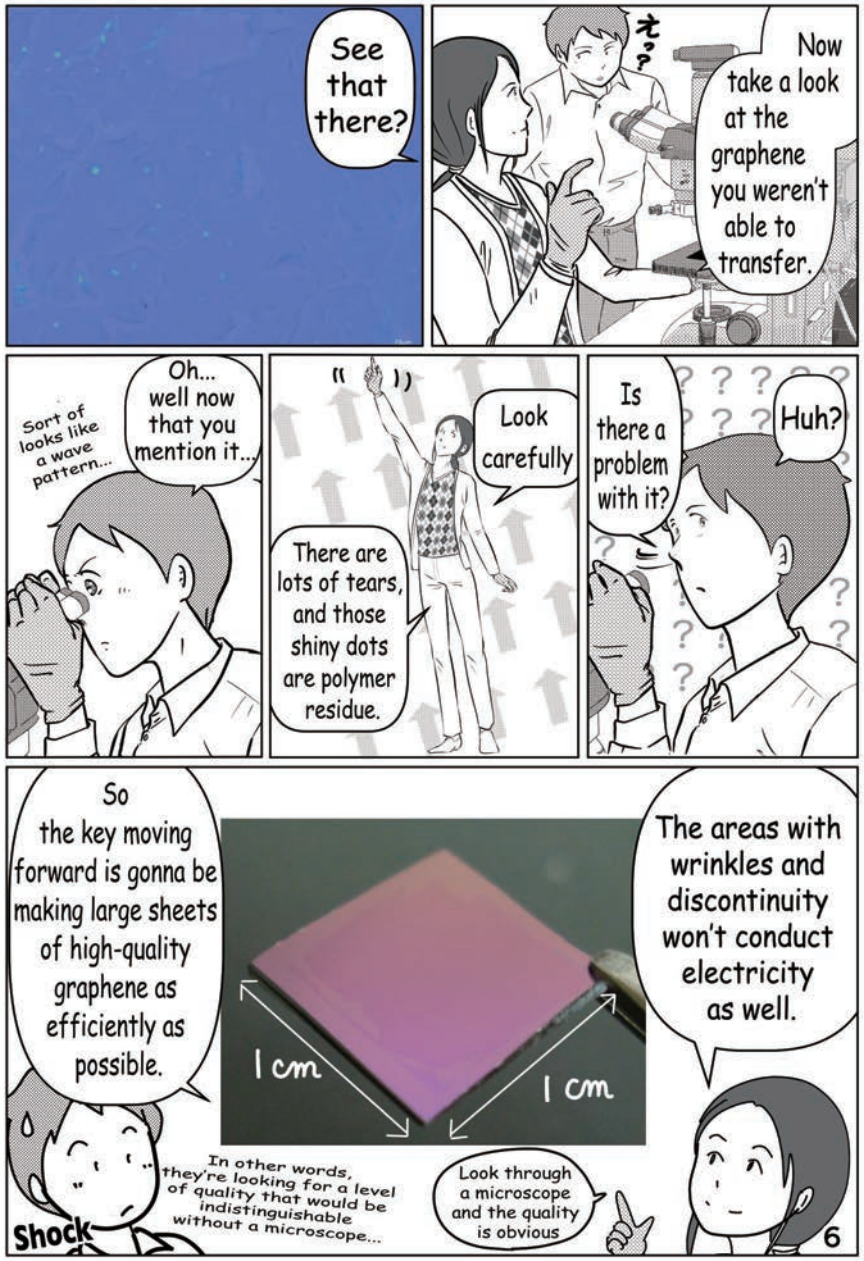
He returns to Kasuga University, confident that the CVD method, which produces large-sea graphene, would allow even him—in all his clumsiness—to pass the test.

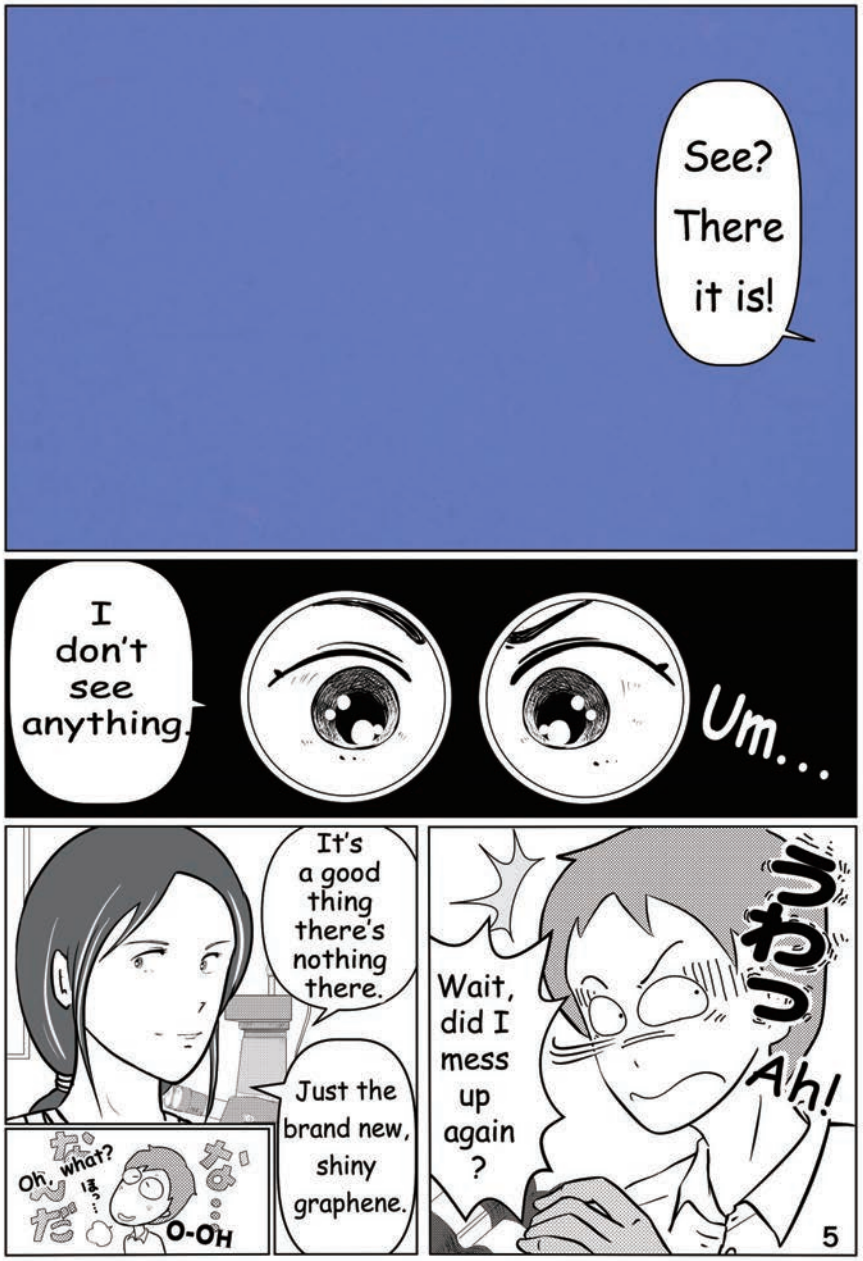
Again, however, he finds himself schooled in the meticulous expertise that goes into graphene production.

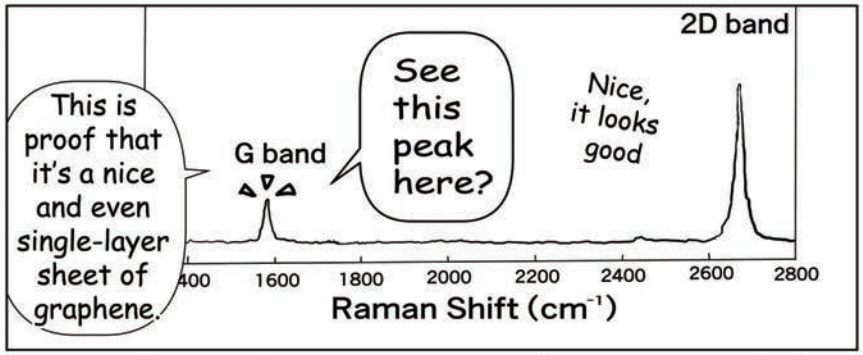
Having finally produced some graphene, he finds himself again at a loss, this time due to his inability to transfer the graphene to a substrate.

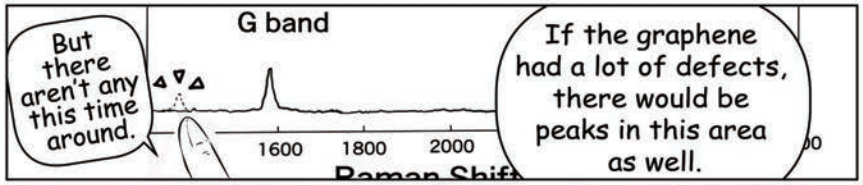

I I got it!!! I did it!
やった!!
Yay!!!
I GOT THE GRAPHENE!
And let's look at it with the microscope.
What!?
Now, put it here.
Pass!
Well, just watch.
Hahaha
But it's so big. Do we really have to use the microscope this time?
Honestly just scared of the microscope
4

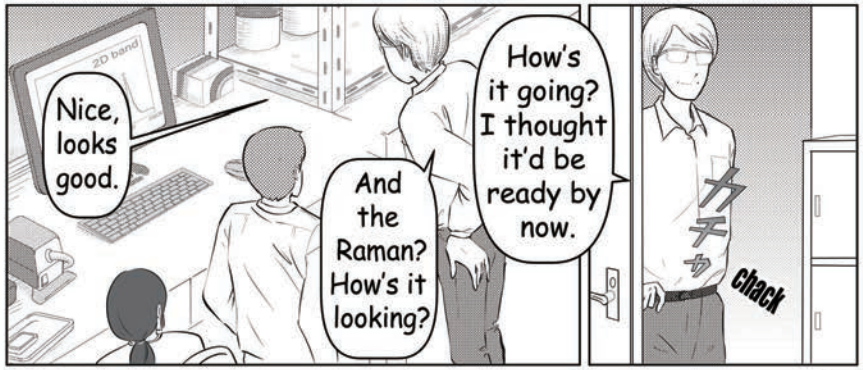

Phew... I'd say yeah, 100%.
She's definitely sussed out how easy I thought CVD wouldbe...
how difficult the CVD method is too.
But I'm thinking maybe now, you understand
I always forget how clumsy I am and get real full of myself.
Okay, deep breath..
I need to get it on the silicon substrate properly.
Maybe if I scoop from deeper down...
3

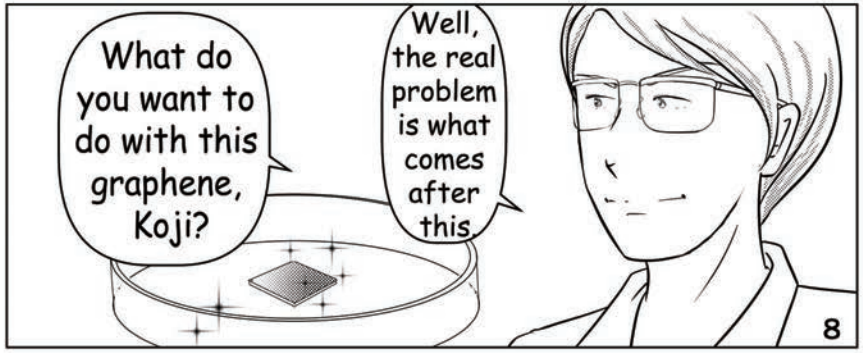

See that there?
Now take a look at the graphene you weren't able to transfer.
Oh... well now that you mention it...
Sort of looks like a wave pattern...
Look carefully
There are lots of tears, and those shiny dots are polymer residue.
Huh?
Is there a problem with it?
So the key moving forward is gonna be making large sheets of high-quality graphene as efficiently as possible.
1 cm
1 cm
The areas with wrinkles and discontinuity won't conduct electricity as well.
In other words, they're looking for a level of quality that would be indistinguishable without a microscope...
Look through a microscope and the quality is obvious
Shock
6


See? There it is!
I don't see anything.
Um...
It's a good thing there's nothing there.
Just the brand new, shiny graphene.
Oh, what?
O-OH
Wait, did I mess up again?
Ah!
5

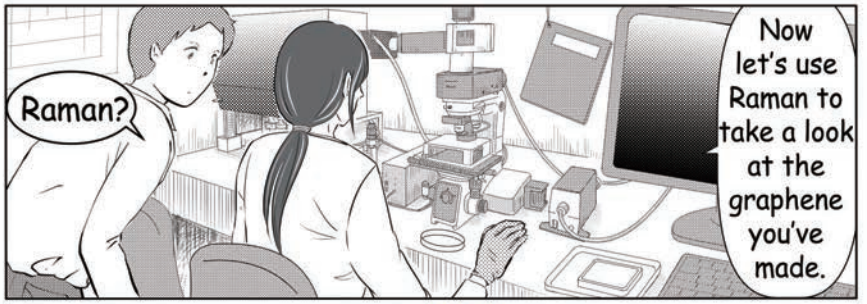

2D band
This is proof that it's a nice and even single-layer sheet of graphene.
G band
See this peak here?
Nice, it looks good
1600
1800
2000
2200
2400
2600
2800
Raman Shift (cm⁻¹)

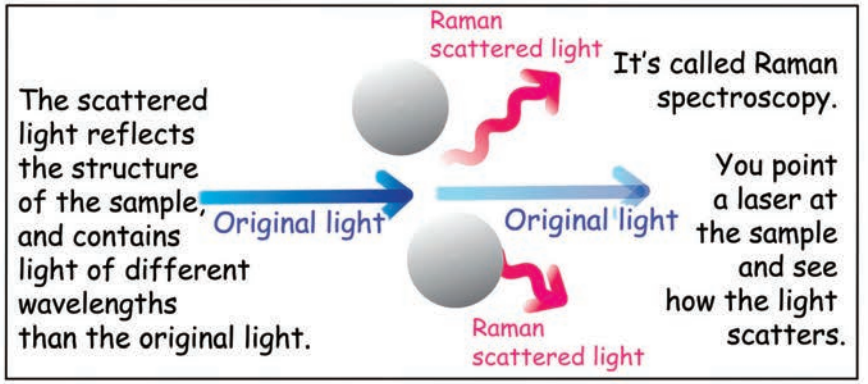

But there aren't any this time around.
G band
1600
1800
2000
If the graphene had a lot of defects, there would be peaks in this area as well.

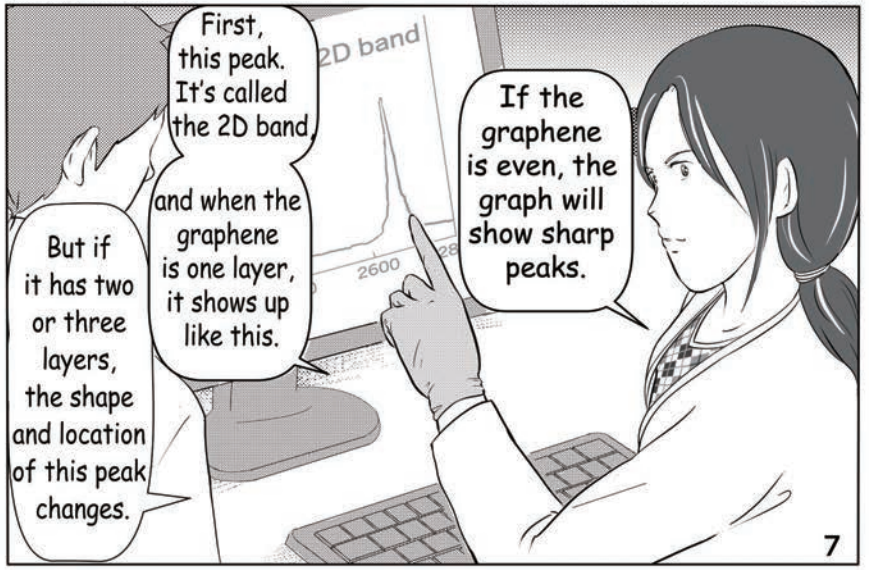

Nice, looks good.
And the Raman? How's it looking?
How's it going? I thought it'd be ready by now.
カチャ
Chack


What do you want to do with this graphene, Koji?
Well, the real problem is what comes after this.

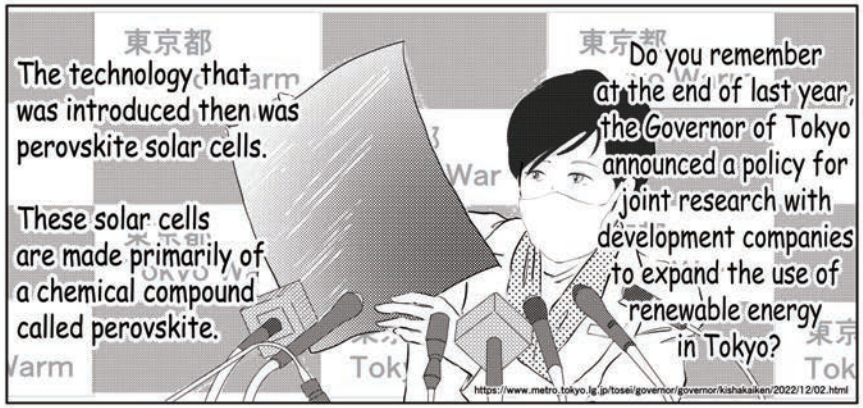
8

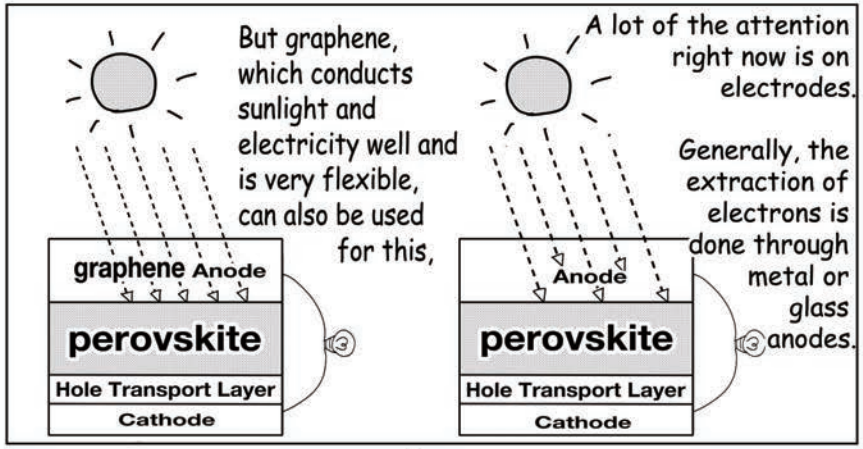

Raman?
Now let's use Raman to take a look at the graphene you've made.

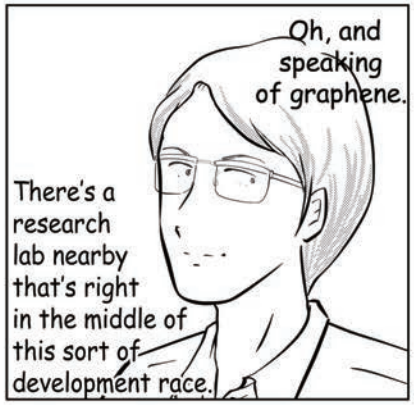

The scattered light reflects the structure of the sample, and contains light of different wavelengths than the original light.
Raman scattered light
Original light
Original light
Raman scattered light
It's called Raman spectroscopy.
You point a laser at the sample and see how the light scatters.

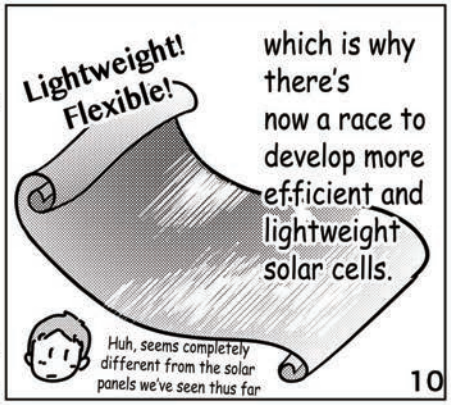

First, this peak. It's called the 2D band.
2D band
2600
and when the graphene is one layer, it shows up like this.
But if it has two or three layers, the shape and location of this peak changes.
If the graphene is even, the graph will show sharp peaks.

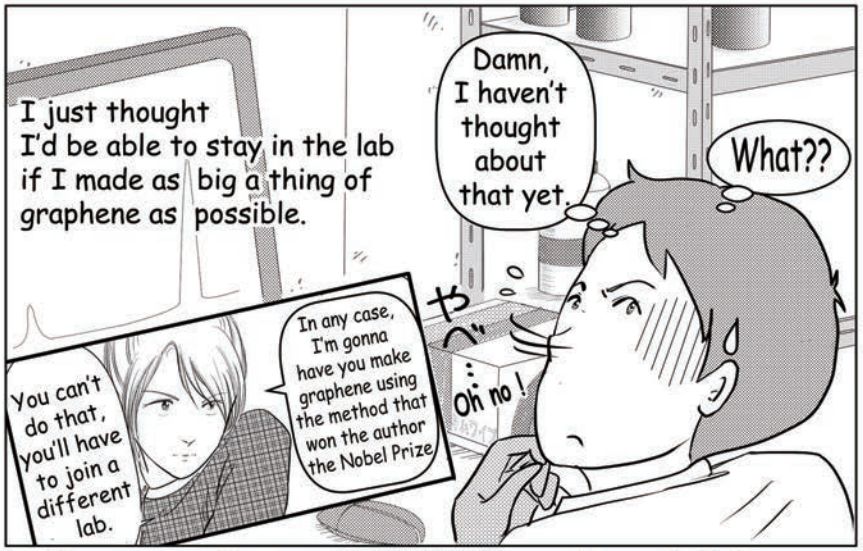
7


Do you remember at the end of last year, the Governor of Tokyo announced a policy for joint research with development companies to expand the use of renewable energy in Tokyo?
https://www.metro.tokyo.lg.jp/tosei/governor/governor/kishakaiken/2022/12/02.html
The technology that was introduced then was perovskite solar cells.
These solar cells are made primarily of a chemical compound called perovskite.


But graphene, which conducts sunlight and electricity well and is very flexible, can also be used for this,
graphene Anode
perovskite
Hole Transport Layer
Cathode
A lot of the attention right now is on electrodes.
Generally, the extraction of electrons is done through metal or glass anodes.
Anode
perovskite
Hole Transport Layer
Cathode


Oh, and speaking of graphene.
There's a research lab nearby that's right in the middle of this sort of development race.

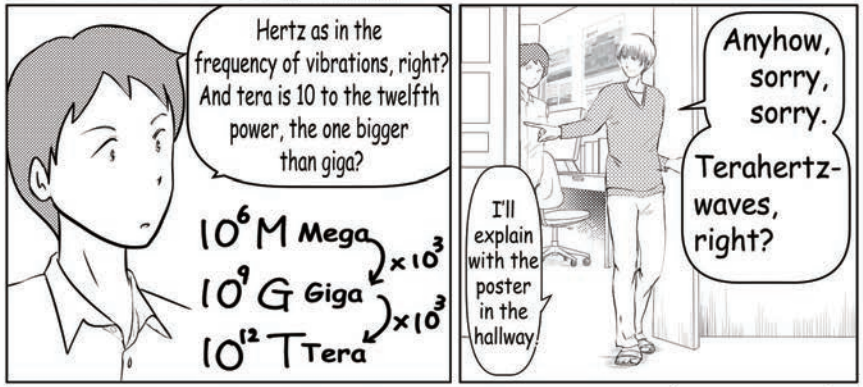

Lightweight!
Flexible!
which is why there's now a race to develop more efficient and lightweight solar cells.
Huh, seems completely different from the solar panels we've seen thus far

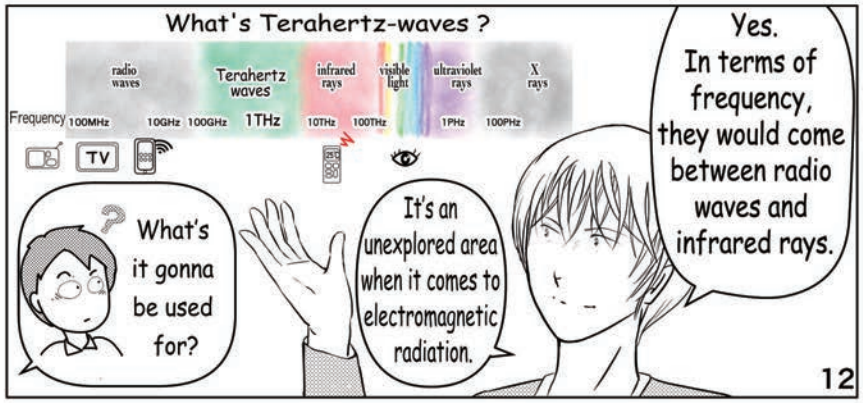

I just thought I'd be able to stay in the lab if I made as big a thing of graphene as possible.
Damn, I haven't thought about that yet.
What??
Oh no!
In any case, I'm gonna have you make graphene using the method that won the author the Nobel Prize
You can't do that, you'll have to join a different lab.

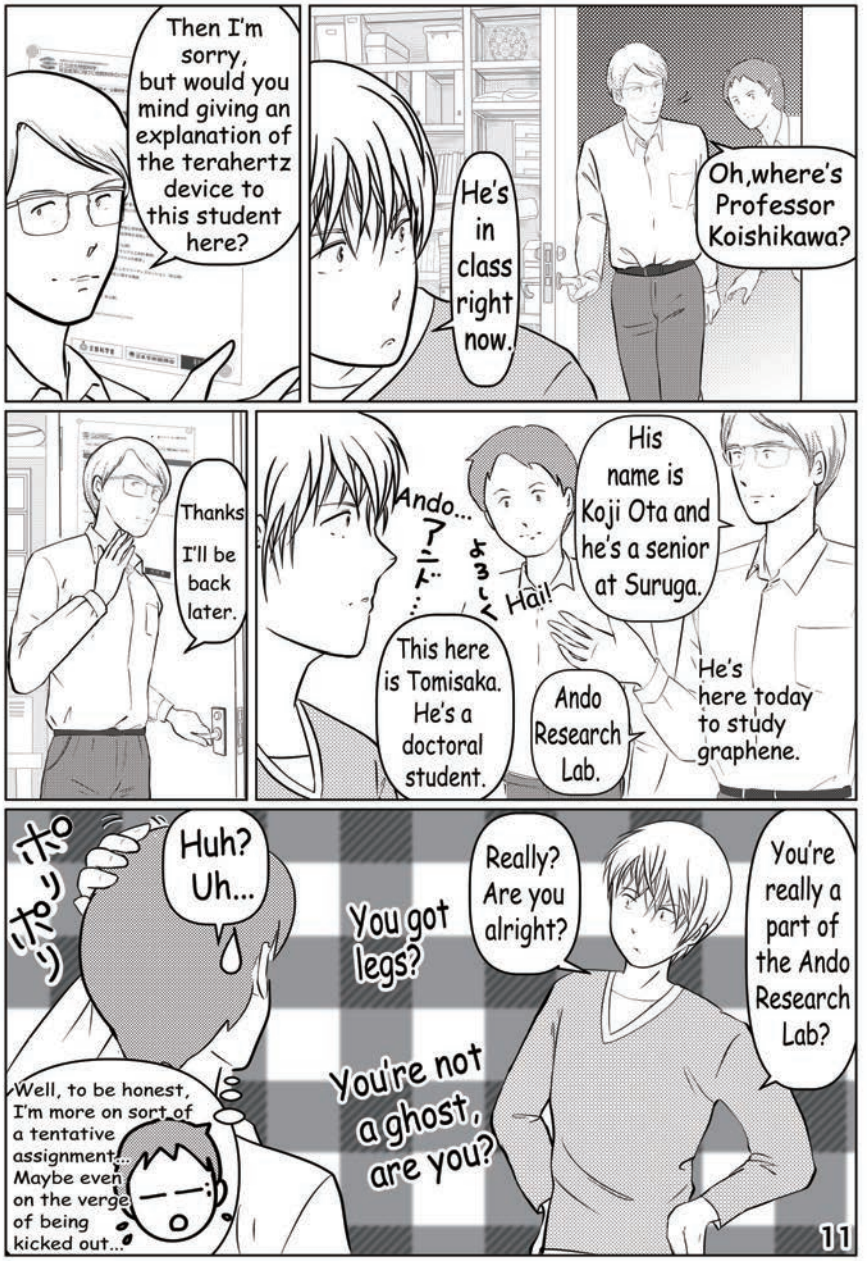

Hey, I dodged that pretty good!
Playing it cool
Uh... Well, what are the topics that are getting the most attention right now?


Graphene is a cutting-edge material that might end up being a game changer in the race for technological development.


T-Those aren't compliments, are they?
Probably thinks of me like a cat running out onto the street...
eek
Or maybe just reckless?
A daredevil? Impressive, whatever it is...
Damn.
You've got guts.
はぁ


Hertz as in the frequency of vibrations, right? And tera is 10 to the twelfth power, the one bigger than giga?
10^6 M Mega
10^9 G Giga
10^{12} T Tera
×10³
×10³
I'll explain with the poster in the hallway.
Anyhow, sorry, sorry.
Terahertz-waves, right?


What's Terahertz-waves ?
radio waves
Terahertz waves
infrared rays
visible light
ultraviolet rays
X rays
Frequency
100MHz
10GHz
100GHz
1THz
10THz
100THz
1PHz
100PHz
TV
What's it gonna be used for?
It's an unexplored area when it comes to electromagnetic radiation.
Yes. In terms of frequency, they would come between radio waves and infrared rays.
12


Then I'm sorry, but would you mind giving an explanation of the terahertz device to this student here?
He's in class right now.
Oh,where's Professor Koishikawa?
Thanks I'll be back later.
Ando...
アンドー...
よろしく
Hai!
His name is Koji Ota and he's a senior at Suruga.
This here is Tomisaka. He's a doctoral student.
Ando Research Lab.
He's here today to study graphene.
ポリポリ
Huh? Uh...
You got legs?
Really? Are you alright?
You're really a part of the Ando Research Lab?
Well, to be honest, I'm more on sort of a tentative assignment... Maybe even on the verge of being kicked out...
You're not a ghost, are you?
11

I guess that's true...

Gah!!

No! Again!

You'd think so. But with X-rays you're exposing yourself to unnecessary radiation.

The properties of terahertz-waves mean that they reflect off the metal of something like a weapon.

Uhhh, I don't have anything like that!

... which pose no harm to the human body, come in.

That's where terahertz-waves...

radio waves

Infrared rays

Terahertz-waves

Areas where the teraherts-waves were reflected (White)

Other areas where the terahertz-waves penetrated (Black)

It'll show a paper clip inside of an envelope like this, for instance.

Paper clip inside envelope

Optimized series

Y (mm)

X (mm)

PTE response (μV)

Fluoroscopic image

K. Li, et al. Advanced Photonics Research 2021, 2, 2000095

Whoa, so clear!

And if your bag gets flagged in the X-ray, they'll open it up and look carefully through the contents.

What's?

Beep Beep!!

For example, before getting on a plane, you go through a security check.

If they could detect hazardous items more clearly, they'd be relieved of that time and effort.

What could have set it off?

murmur

What's?

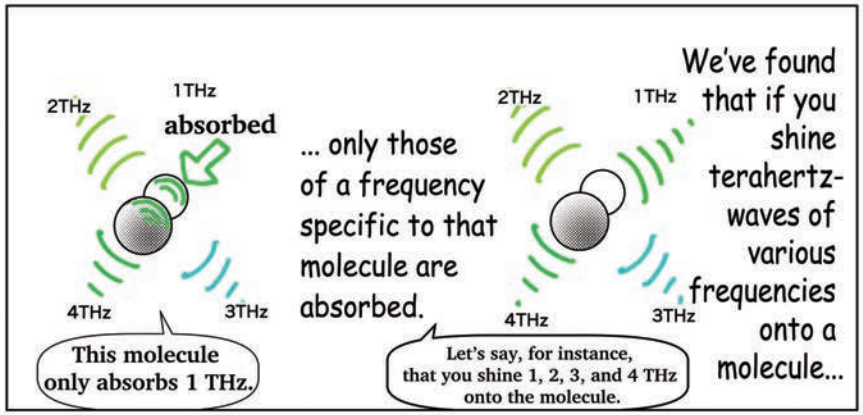
This takes a really long time.

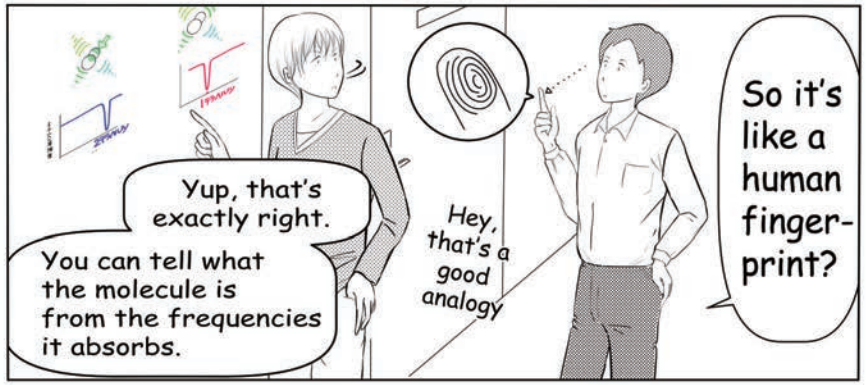
Can't you already see everything with that anyway?

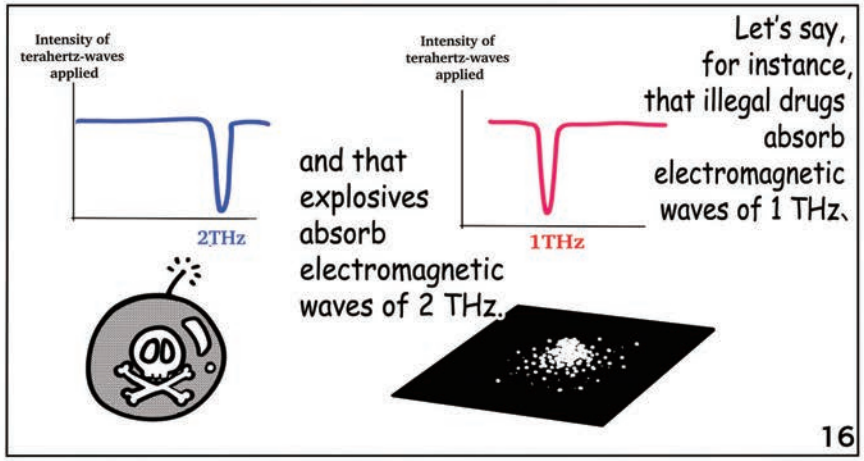
Isn't the security check at the airport an X-ray?

Note: The security scan doesn't actually show the bones.

Terahertz-waves can solve this problem.

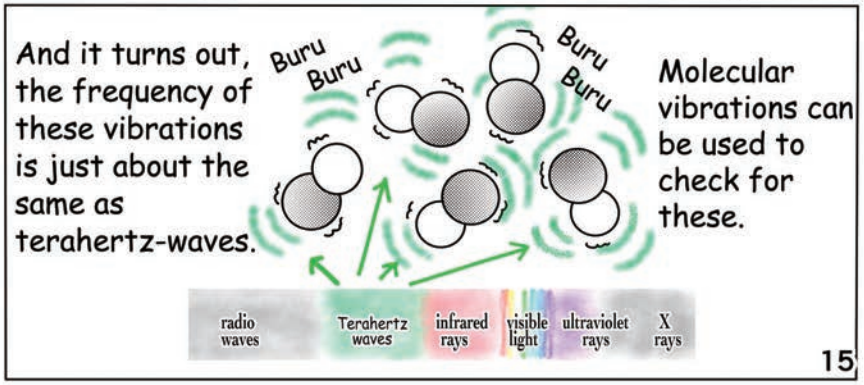

2THz
1THz
absorbed
4THz
3THz
This molecule only absorbs 1 THz.
... only those of a frequency specific to that molecule are absorbed.
2THz
1THz
4THz
3THz
Let's say, for instance, that you shine 1, 2, 3, and 4 THz onto the molecule.
We've found that if you shine terahertz-waves of various frequencies onto a molecule...

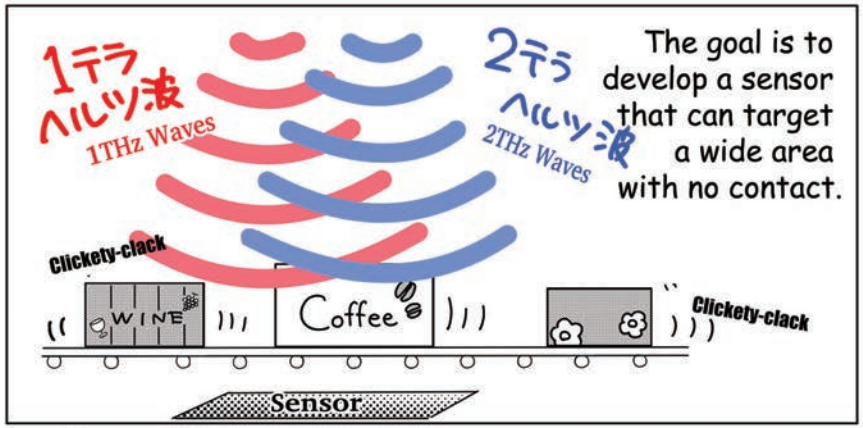

Yup, that's exactly right.
You can tell what the molecule is from the frequencies it absorbs.
Hey, that's a good analogy
So it's like a human finger-print?


Intensity of terahertz-waves applied
2THz
Intensity of terahertz-waves applied
1THz
Let's say, for instance, that illegal drugs absorb electromagnetic waves of 1 THz、
and that explosives absorb electromagnetic waves of 2 THz.

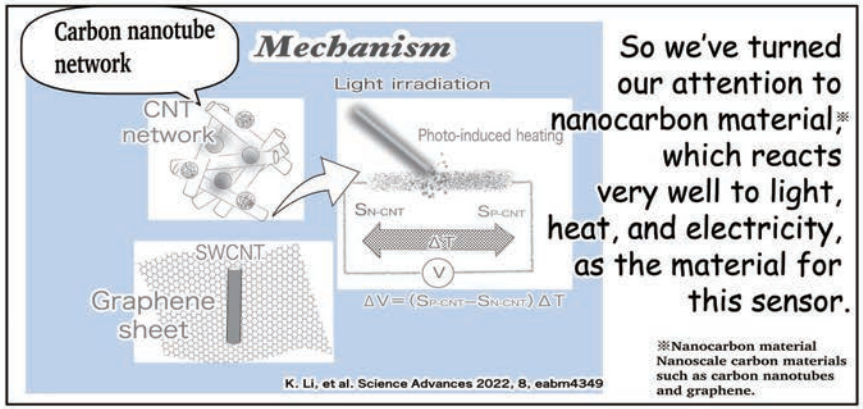

Damn, they found it.
In other words, terahertz-waves have the penetration of X-rays, and gives a clear view of what's inside and are also harmless.


They also need to watch out for illegal drugs or plants that are import prohibited.
What's more, it's not like knives and other weapons are the only things they check for at airports.


And it turns out, the frequency of these vibrations is just about the same as terahertz-waves.
Buru Buru
Buru Buru
Molecular vibrations can be used to check for these.
radio waves
Terahertz waves
infrared rays
visible light
ultraviolet rays
X rays

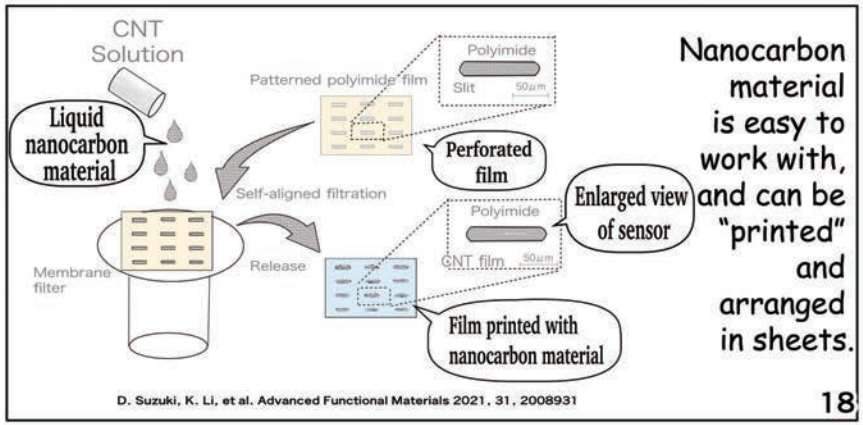


The goal is to develop a sensor that can target a wide area with no contact.



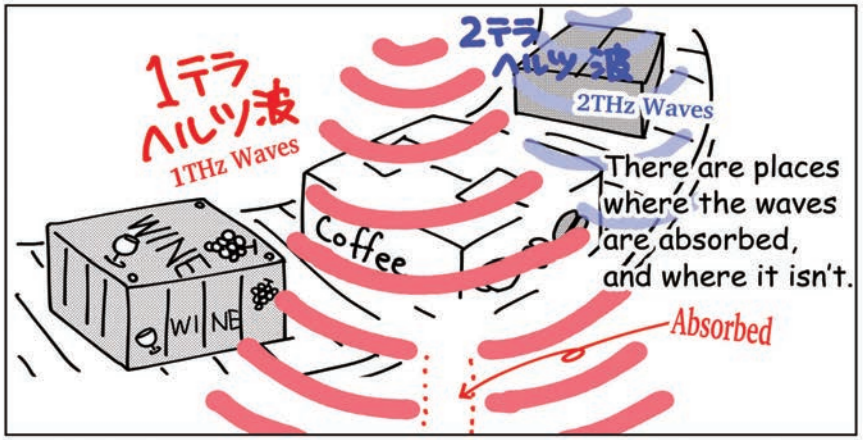
So we've turned our attention to nanocarbon material※ which reacts very well to light, heat, and electricity, as the material for this sensor.

※Nanocarbon material
Nanoscale carbon materials such as carbon nanotubes and graphene.

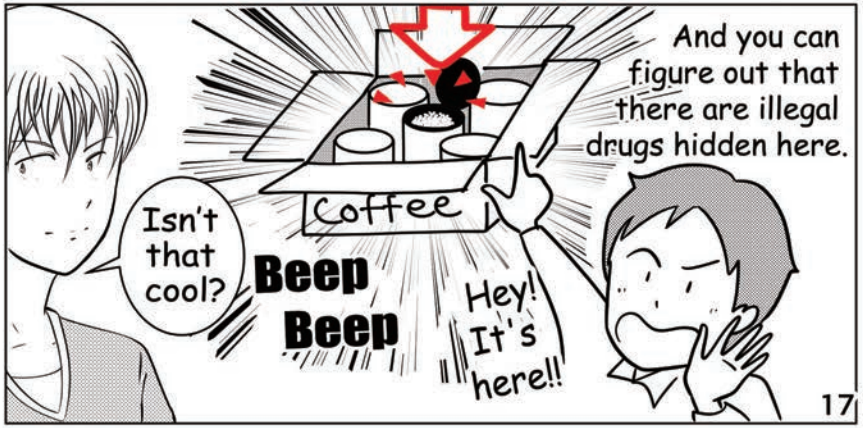


Nanocarbon material is easy to work with, and can be "printed" and arranged in sheets.

If you shine terahertz-waves onto an area where there are a lot of different materials...



There are places where the waves are absorbed, and where it isn't.



And you can figure out that there are illegal drugs hidden here.

※https://www.mlit.go.jp/sogoseisaku/maintenance/02research/02_01.html

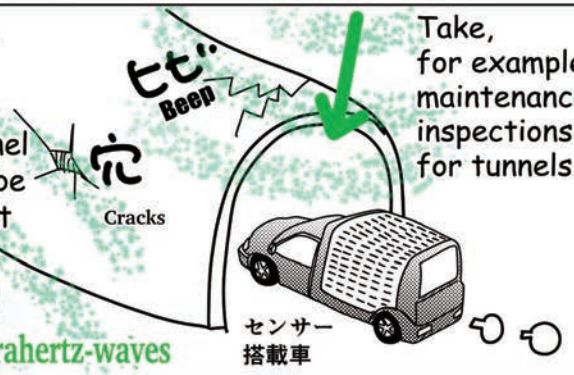
It's predicted that the social infrastructure that was developed intensively during Japan's period of rapid economic growth...

... will all deteriorate at once over the next 20 years.

The maintenance of this infrastructure is now an urgent social issue.

Driving a vehicle equipped with these sensors through the tunnel just once would be enough to inspect the entirety of the tunnel.

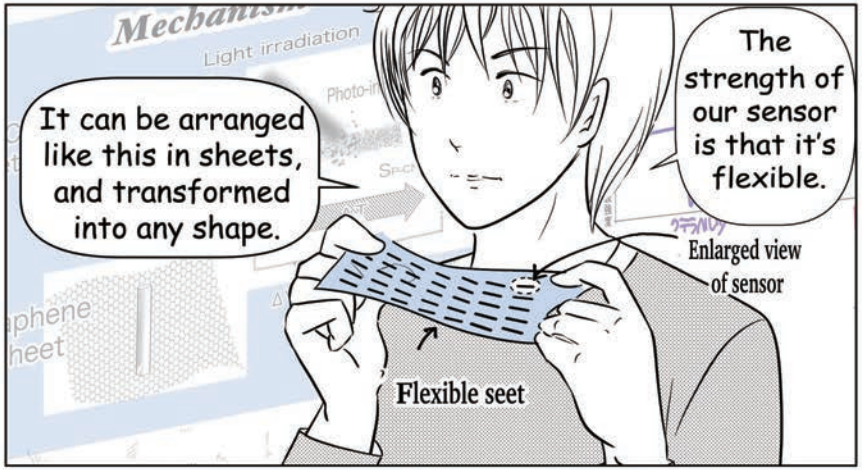
Take, for example, maintenance inspections for tunnels.

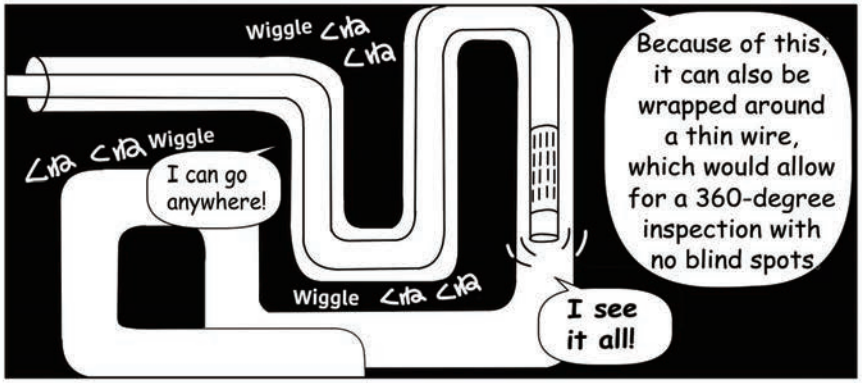


Inspections without blind spots are really hard.

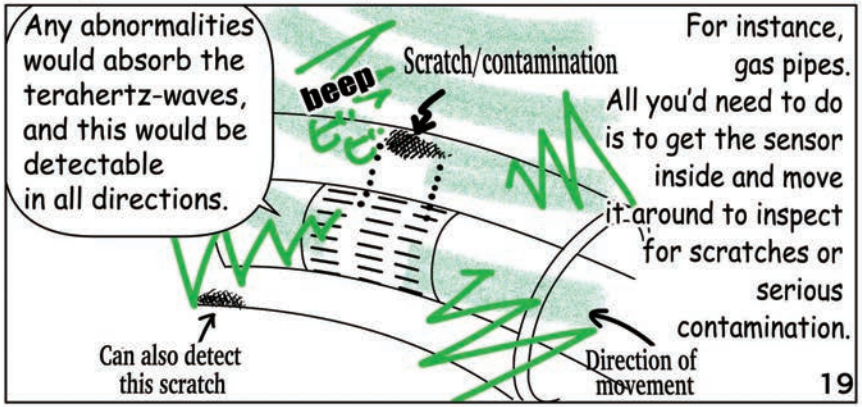
That would be truly tedious, and would take a lot of time.

If this were a rigid, or more limited sensor, you'd have to change the direction of the sensor as you moved along.





Any abnormalities would absorb the terahertz-waves, and this would be detectable in all directions.



For instance, gas pipes. All you'd need to do is to get the sensor inside and move it around to inspect for scratches or serious contamination.

Cooling device + Sensor

Heavy! Gets in the way!

There are some terahertz-wave sensors that need to be cooled to have this property...

... but it's of course better to be able to use it at temperatures you would find in everyday life.

That's why nanocarbon material is getting all this attention right now as a material that can be used for these terahertz-waves.

NTT

Realizing Zero-Bias Operation of a Graphene Photodetector at 220 GHz and Elucidating the Optical-to-Electrical Conversion Process: Demonstrating the Promise of Graphene as a Broadband High-Speed Photodetector Material

世界最速、グラフェン光検出器のゼロバイアス動作220 GHzの実現と光-電気変換プロセスの解明
～広帯域高速光検出器材料としてのグラフェンの有望性を実証～

光検出器の活用分野

イメージング　分光　センシング

光検出器に必要な性能

広帯域 高感度	広帯域 高感度	高速 高感度

■ 世界最速、220GHz動作を実現
■ これまでわからなかった高速物性を世界で初めて解明

https://group.ntt/jp/newsrelease/2022/09/12/220912a.html

東北大学 TOHOKU UNIVERSITY

Press Release

RIKEN

2022年12月15日

報道機関 各位

東北大学電気通信研究所
理化学研究所

新原理グラフェントランジスタによる高速・高感度テラヘルツ波の検出に成功
次世代6G&7G超高速無線通信の実現に明るい光

【発表のポイント】
・従来原子の単層シートであるグラフェンを使い、室温下で高速応答かつ高感度なテラヘルツ波[注1]の検出に成功した。
・単一の金属種で全ての電極を形成する最も単純なグラフェントランジスタ構造でも高速・高感度検出ができる新たな検出原理を発見した。
・6G、7G[注2]クラスの次世代超高速テラヘルツ無線通信の実現に貢献すると期待される。

【概要】
炭素原子の単原子層材料であるグラフェンは、電子の有効質量[注3]がゼロなどの特異な物性を有することから、従来の技術では困難な室温で動作する高速応答かつ高感度なテラヘルツ波検出素子を実現する材料として注目されています。

東北大学電気通信研究所の佐藤昭准教授らと理化学研究所光量子工学研究センターの南出泰亜チームリーダーらの研究グループは、グラフェンを使って、室温で動作する高速応答かつ高感度なテラヘルツ波の検出に成功しました。テラヘルツ波の高速・高感度な検出素子として、電磁波吸収で発熱した電子・正孔の空間拡散で生じる起電圧効果を利用する「光電熱型検出素子」が知られていますが、電子・正孔の両方が寄与する複雑なバイポーラ型[注4]でかつ検出素子の2つの電極に異種材料を用いなければ起電圧が生じず、高性能化と量産化・低コスト化の両立が極めて困難でした。研究グループは、グラフェンをチャネルとする電子のみが関与するユニポーラ型[注4]で、かつ全ての電極に同一種の金属を用いる単純なトランジスタ素子構造でも検出動作可能な、新たな原理を見い出し、高速・高感度なテラヘルツ波検出に初めて成功しました。次世代6G&7G超高速無線通信実現のブレークスルーとなる画期的な成果です。

本成果は、米国物理学協会（American Institute of Physics）が発行するオープンアクセス国際学術論文誌 APL Photonics にFeatured Article*として2022年12月2日にオンライン掲載されました。

*編集委員会により特に学術的意義・インパクトが高いと評価された論文

Success in High-Speed, High-Sensitivity Terahertz Detection Using a Graphene Transistor: A Bright Light of Hope Towards the Realization of Next-Generation 6G and 7G Ultra-High-Speed Wireless Communication

https://www.tohoku.ac.jp/japanese/newimg/pressimg/tohokuuniv-press20221215_02web_th.pdf

... would be truly wonderful for modern society.

This is my one focus here at graduate school.

Being able to conduct these inspections **without having to stop electricity, disrupt logistics, or disassemble anything...**

He seems reserved but he's actually really passionate about this.

Wow!

We don't just make the graphene and then we're done.

CNT Solution

Patterned polyimide film

Polyimide

Slit 50μm

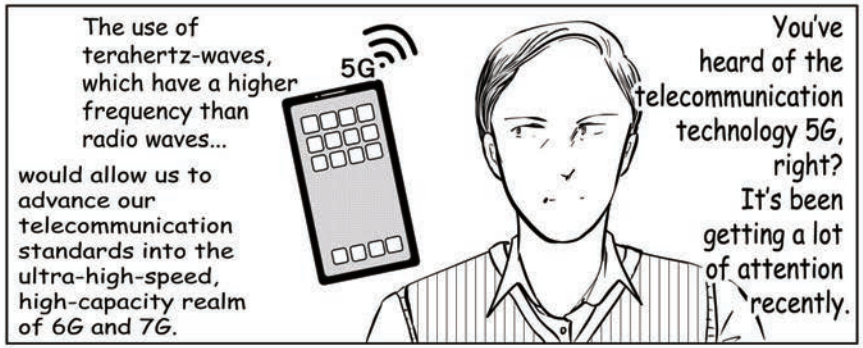
Filtration

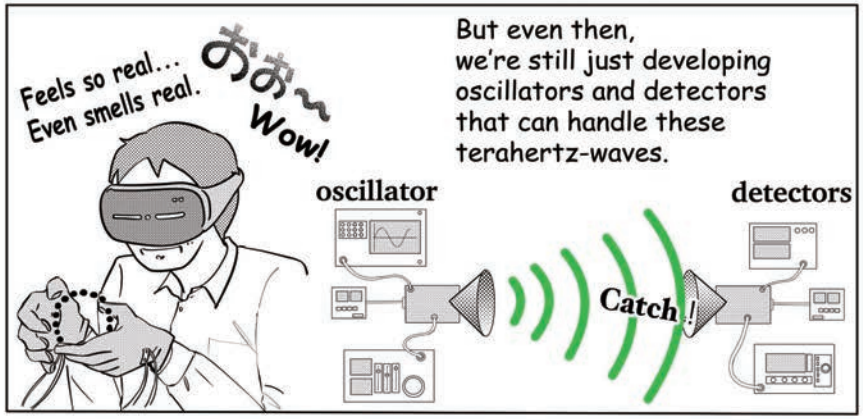
Graphene sheet

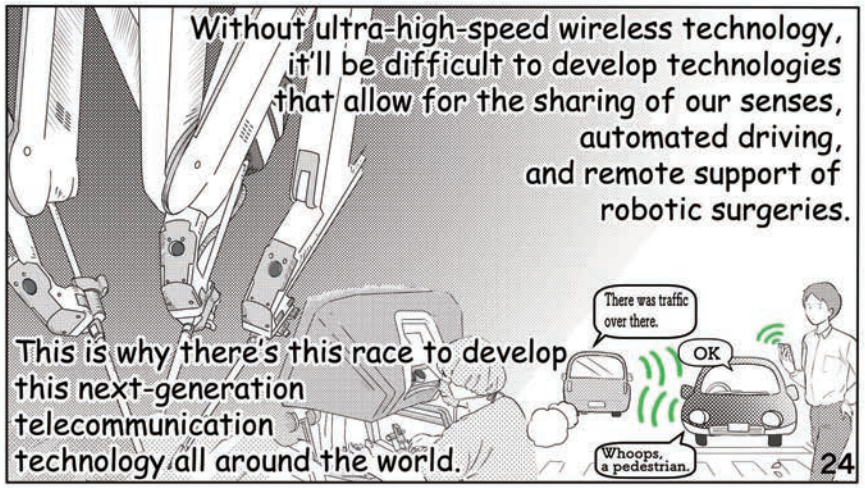
There's more.

I just told you that nanocarbon material can move electrons and electron holes at high speeds, and absorbs a ton of light

But the key here is that it retains this property **even in room temperature.**

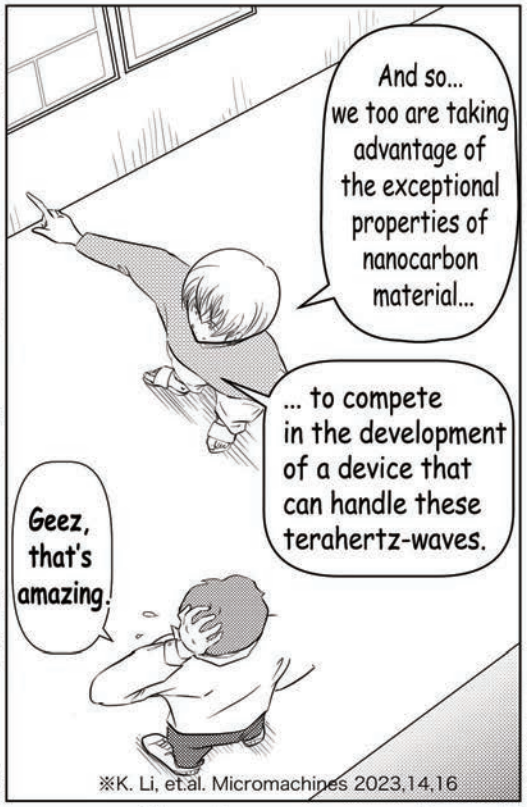

The use of terahertz-waves, which have a higher frequency than radio waves...
would allow us to advance our telecommunication standards into the ultra-high-speed, high-capacity realm of 6G and 7G.
5G
You've heard of the telecommunication technology 5G, right? It's been getting a lot of attention recently.

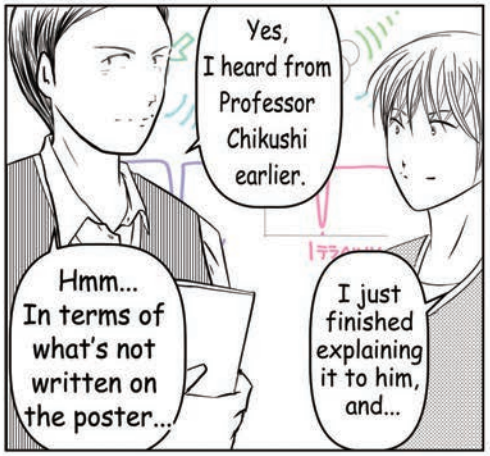

Feels so real... Even smells real.
おぉ～ Wow!
But even then, we're still just developing oscillators and detectors that can handle these terahertz-waves.
oscillator
detectors
Catch!


Without ultra-high-speed wireless technology, it'll be difficult to develop technologies that allow for the sharing of our senses, automated driving, and remote support of robotic surgeries.
This is why there's this race to develop this next-generation telecommunication technology all around the world.
There was traffic over there.
OK
Whoops, a pedestrian.
24


Oh, and it's trade secrets from here on out. You might be an undergrad student, but you've gotta keep this a secret.
KEEP OUT
shh


Ah, please, I'm a total beginner so...
... you've got nothing to worry about.
Don't be absurd


And so... we too are taking advantage of the exceptional properties of nanocarbon material...
... to compete in the development of a device that can handle these terahertz-waves.
Geez, that's amazing.
※K. Li, et.al. Micromachines 2023,14,16


Yes, I heard from Professor Chikushi earlier.
Hmm... In terms of what's not written on the poster...
I just finished explaining it to him, and...


An impromptu poster session?
Oh, professor.
Oh, hello.
23

Supervised ; Group A01 Hiroki Ago, Professor, Global Innovation Center, Kyushu University, Group A05 Yukio Kawano, Professor & Kou Li, Assistant Professor, Faculty of Science and Engineering, Chuo University, For more information https://25d-materials.jp