

Surface Enhanced Raman Scattering Spectroscopy

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Abstract

This review covers from the basic principles of Raman spectroscopy to the advanced technique of surface enhanced Raman Scattering (SERS) spectroscopy. After briefly going through the description of Raman and introduction of the development of SERS, the article will focus on the “hotspot” of the current research work on SERS – single molecule spectroscopy. We will see later that “hotspot” is also frequently used to describe the place where SERS happens. This vague description in some extent reflects the ambiguity and controversy in the understanding of the phenomenon. However, single molecule SERS provides us a possible way to disclose the secret.

Single molecule spectroscopy is not only a novel tool to explore the properties of the molecules; it also shines light on the further understanding the SERS itself. Research work from several groups in this field was introduced. There are lots of other applications for SERS in the bioscience, which is beyond the scope of this short paper. Only the application of SERS studying the surface adsorption and detection of DNA and RNA were presented to give some flavors in this research field.

Finally, what can we do with SERS? In the last part of the paper, the topic of doing SERS on the flat surface was discussed. This is not only of intellectual fun, but may also give us great advantages to develop new techniques. One example is to combine the SERS with surface force apparatus (SFA) study, which requires two smooth flat surfaces. Unfortunately smooth flat surface is the killer of the enhancement. Then here we try to rescue.

Only little mathematics was given for the illustration of the principles of Raman. The electromagnetic explanation of SERS will definitely be demonstrated better with equations, which however falls beyond my background and knowledge.

At last, two references are strongly recommended to those who want a good introductory but not too out-of-date material. One is the handout for MIT class by Katrin Kneipp. She is one of the earliest researchers who work on the single molecule SERS. Another is a free online journal called “the internet journal of vibrational spectroscopy” with a featured issue on SERS. Here is the link:

<http://www.ijvs.com/volume4/edition2/index.html>

Introduction

1. Raman scattering

1.1. Classical explanation ^[1]

Light is treated as a electromagnetic wave and the molecules is modeled as small spheres connected by the spring as shown in the figure 1:

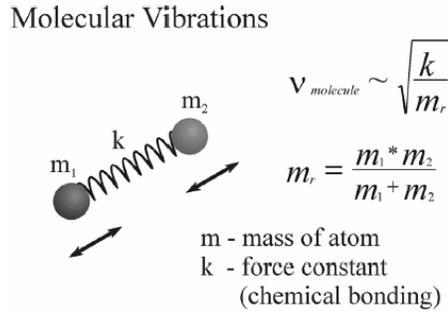


Figure 1. Model for the molecules

The incident light can be described by the following equation:

$$E(x,t) = E_0 \cos(\omega t - kx)$$

The induced dipole is:

$$\mu = \alpha \cdot E$$

α is the polarizability tensor,

Substitute in the electric field of light,

$$\mu = \alpha \cdot E_0 \cdot \cos(\omega_L t)$$

The polarizability tensor depends on the conformation of the molecule; it changes as the molecule vibrates,

$$\alpha = \alpha(Q), \text{ Q is the vibrational coordinate,}$$

We can Taylor expand α and get,

$$\alpha = \alpha_0 + \left[\frac{\partial \alpha}{\partial Q} \right] \cdot Q + \dots, \text{ Where}$$

$$Q = Q_0 \cdot \cos(\omega_M t),$$

By substitute α , we can calculate the induced dipole,

$$\mu = \alpha \cdot E_0 \cdot \cos(\omega_L t) + \left[\frac{\partial \alpha}{\partial Q} \right] \cdot Q_0 \cdot E_0 \cdot \cos(\omega_M t) \cdot \cos(\omega_L t)$$

$$\mu = \alpha \cdot E_0 \cdot \cos(\omega_L t) + \left[\frac{\partial \alpha}{\partial Q} \right] \cdot Q_0 \cdot E_0 \{ \cos[(\omega_L - \omega_M)t] + \cos[(\omega_L + \omega_M)t] \}$$

From the equation we can see that, the three terms represent three different frequency of the emitted light. The first term shows the frequency of the emission light is the same with the incident light, which is called the Rayleigh scattering. For the second and third term, there is a shift of the frequency of the emitted light from the incident light, which is called Stokes scattering and anti-Stokes scattering accordingly.

Finally we can get the intensity of the Raman scattering,

$$I_{\text{stokes}} \sim (\omega_L - \omega_w)^4 \cdot \left(\frac{\partial \alpha}{\partial Q} \right)^2 \cdot I_0(\omega_L),$$

$$I_{\text{stokes}} \sim (\omega_L - \omega_w)^4 \cdot \left(\frac{\partial \alpha}{\partial Q} \right)^2 \cdot I_0(\omega_L) \cdot e^{-\frac{h\nu_M}{kT}}$$

1.2. Quantum explanation ^[1, 2]

From the classical point of view the derivation of Raman scattering is straightforward from mathematics, while the quantum explanation is more pictorial and fits better with the appetite of chemist.

When the energy of the incident light is not large enough to excite the molecules from the ground state to the lowest electronic state, the molecule will be excited to a virtual state between the two states. The electron cannot stay long in the virtual state and will immediately go back to the ground state. If the electron goes to where it is originated from, then the wavelength of the scattered light is the same as the light source, which is called Rayleigh scattering. It is also possible that the electron goes to the vibrational state different from where it is excited, and then there is an energy difference between the emitted photon and the incident photon. If the emitted energy is smaller than the incident energy, the process is called the Stokes scattering. The opposite is called the anti-Stokes scattering.

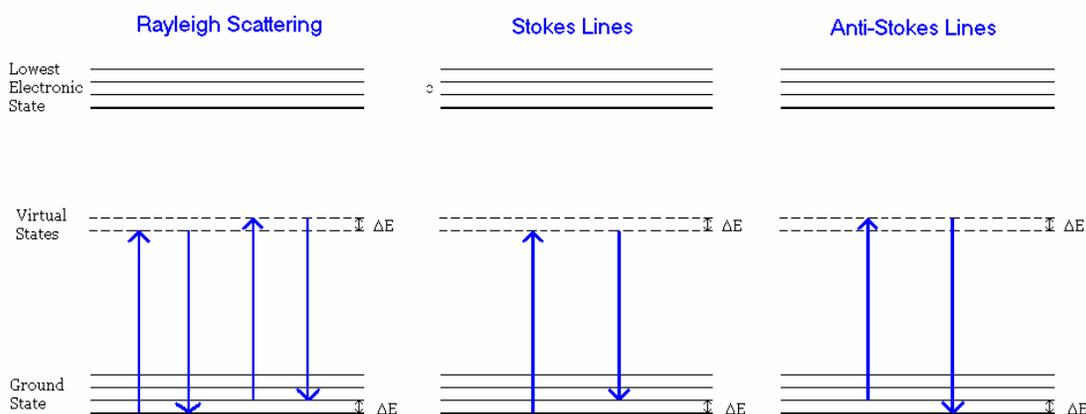


Figure 2. The quantum illustration for different cases of scattering

1.3. Harmonious picture

Both classical and quantum mechanical view of the Raman scattering have some advantages in understanding the Raman spectroscopy. Though the quantum picture is more vivid, it involves the understanding of the virtual state and is hard to calculate. The classical description is more straightforward and provides some quantitative relationships. In this sense people use classical explanation more and further develop it to explain the mechanism of the surface enhanced phenomenon.

However from the quantum point view we can develop the concept of *cross section*, which represents the possibility of photon interact with the molecules. The cross section will directly change the intensity of the emission.

Figure 3 shows the quantum description of Raman, Fluorescence and IR and their spectrum accordingly.

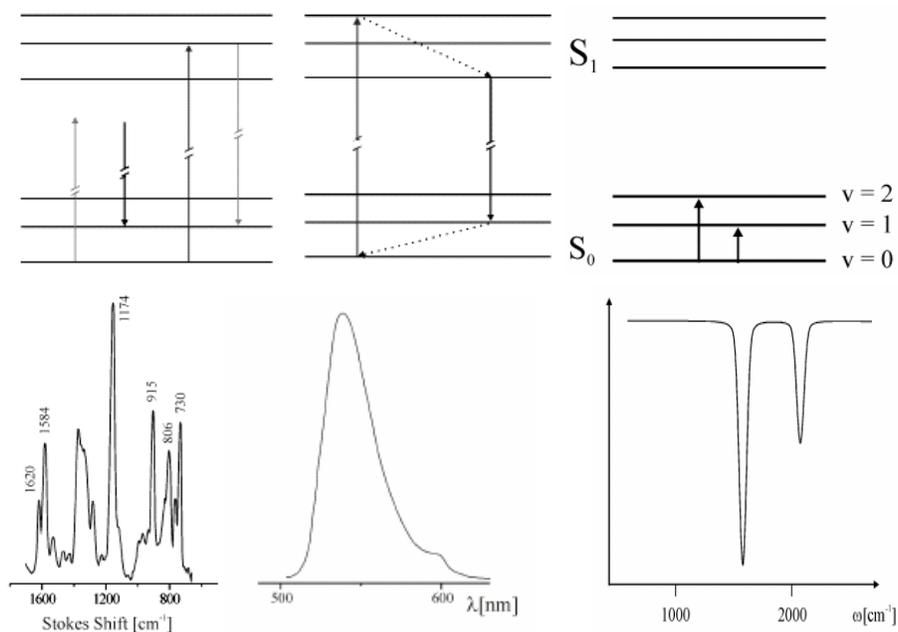


Figure 3. The comparison of different scatterings

Fluorescence involves the relaxation of the vibration, while Raman is sensitive to different vibrational modes. Therefore Raman is more sensitive than fluorescence and is called the fingerprint of the molecules.

IR is a complementary technique to Raman. IR sensitive requires μ changes as the molecule vibrates, while Raman requires the change of α .

Another important factor is that the cross section for Raman is much smaller than that of the fluorescence. The cross section for fluorescence is about 10^{-16} cm² per molecule, but Raman only has $10^{-31} \sim 10^{-26}$ cm² per molecule. This is the biggest disadvantage of Raman and is also the reason why Raman was not widely used for a long time, until the surface enhanced Raman effect was discovered. In this sense, we can call SERS Surface Enhancement Rescued Spectroscopy.

2. Surface Enhanced Raman Spectroscopy

2.1. History of the SERS ^[3]

SERS was accidentally discovered while people tried to do Raman on the electrode in 1974. The original idea was to generate a high surface area on the roughened metal. Gradually people realize surface area is not the key point in this phenomenon. After a period of search in the dark, the progress was made in 1977 when different groups found the rough silver electrode produce a Raman spectrum that is a million fold more intense than what was expected. This enormously strong signal debuted surface enhanced Raman scattering (SERS). Recently SERS completely overcome the disadvantage of the small cross section of Raman spectroscopy, and could be used to study the single molecule spectroscopy.

2.2. Key features of SERS ^[4]

The key features are summarized briefly as follows:

- SERS occurs when molecules are brought to the surface of metals in a variety of morphologies. The smooth surface is not active for the enhancement.
- Large enhancements are observed from silver, gold and copper. If the metal nanoparticles are used in the system, the particle size for enhancement of Raman to happen ranges from 20nm~300nm.
- Molecules adsorbed in the first layer on the surface show the largest enhancements. However, the enhancement also has long-range effect of about tens of nanometers.
- The excitation profile (scattering intensity vs. exciting frequency) deviates from the fourth-power dependence of normal Raman scattering.

Methods and Analysis

3. Instrumentation

In recent years, the utilization of charge coupled device (CCD) detectors, confocal microscopes, and notch filter in Raman instrumentation, have produced a new generation of Raman instruments, providing very high sensitivity. Together with the SERS this technique enables us to study the single molecule Raman spectroscopy.

3.1. Break the diffraction limit ^[5]

The size of the probed volume by laser is restricted by the diffraction limit. One way to break this diffraction limit is to use the total internal reflection and special near field probes, which take the advantage of evanescent fields.

When the light transfers from an optically dense material to a less dense material ($n_1 > n_2$) with an incident angle greater than the critical angle for total reflection, all light is reflected (total internal reflection). In spite of the fact that the incident energy is totally reflected, there is still an electromagnetic wave field in the region beyond the boundary. This field is known as the evanescent wave. Its existence can be understood by consideration of the wave function of the electric vector of the transmitted wave. And this

electromagnetic field is called an evanescent wave because the intensity of it is an exponential decay versus the distance from the interface.

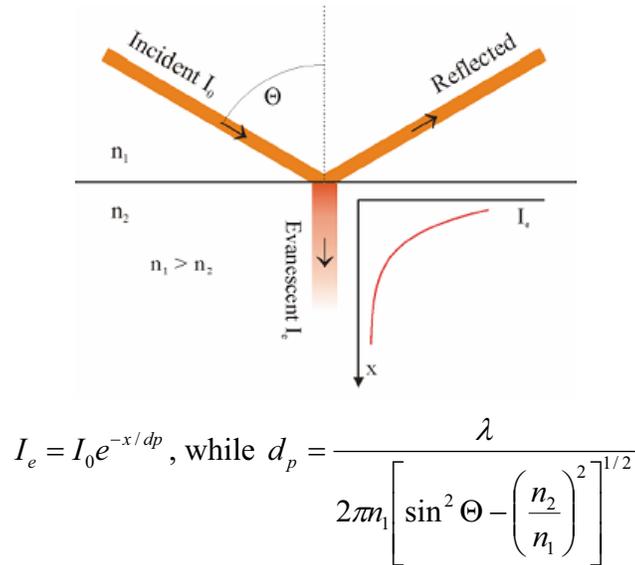


Figure 4. Illustration of internal total reflection

From equation we can see that the illuminated length by the evanescent wave is about half of the wavelength.

4. Synthetic process

On the other hand, besides the optical system, the key point of generating SERS is to make the ideal metal surface. It is found that SERS activity critically depends on the nature of metal and surface roughness; therefore substrate preparation is always of central concern [6]. The two most widely used SERS active substrates are metal colloids (especially aggregated colloids) generated by chemical methods and electrode surfaces roughened by one or more electrochemical oxidation-reduction cycles. The other less common substrates include surfaces roughened by chemical etching in acids, "island films" deposited on glass surfaces at elevated temperatures or surfaces finished by electrochemical deposition from solutions, and films deposited by evaporation or sputtering in vacuum onto cold (100 K) substrates.

In order to illustrate more clearly, here we give a very simple example of preparing the Ag colloidal particles that can be done in the undergraduate laboratory [7]. Let's just brief go through the procedures.

First is the preparation of colloidal Ag particles stock. It involves a reduction reaction of AgNO_3 with NaBH_4 . Then after the nano-particles are obtained, certain amount of salt will be added to the solution. This will increase the ionic strength and cut down the Debye-Hückel length, which causes the colloid particles to aggregate. We will see later in the mechanism section why this is very an important step in obtaining a more active SERS substrate.

In the next step the target molecule (pyridine) will be absorbed onto the colloid surface by simply adding it to the solution while under the vigorous stir. And at last we are in good shape to collect the Raman signal with the optical setup.

The procedure is rather simple and straightforward, however it took some time for people to finally get it. What's more we are still not sure what exact happens when we carry out a SERS experiment. One of the important tasks in the research of the SERS is the study of SERS mechanism.

5. Mechanism of SERS ^[1, 8]

5.1. Physics contribution to the SERS

Several years ago few were fully convinced that SERS enhancement could be as high as 15 orders of magnitude, and SERS active materials would include a variety of transition metals and probably semiconductors. These observations challenge our conventional understanding of SERS and provide some key evidence to the interpretation of the mechanism. In addition this 15 orders of magnitude even enables us to study the Raman spectroscopy of the single molecule, which is not only a powerful spectroscopic tool but also gives us more insight about SERS.

We will first give some descriptive explanation of physics part of the enhancement (the quantitative description is a little beyond my knowledge). And then we will focus on the single molecule spectroscopy to further give some evidence and also to raise some questions about the SERS mechanism.

The physics explanation is built up on the basis the classical description of Raman effect ^[9]. Let's just review the different terms related with the intensity of the Raman spectrum. The enhancement most probably comes from the increase of the electric field. Theoretical calculation for one single particle found that when the shape of the particle was sharp, the electric field near the sharp tip would be greatly enhanced. What's more it is estimated that when two or more particles gather together, the electric field between them will be further enhanced. There could be a collective resonance of the free electron in the surface of the metal particles, which provides great enhancement. Theoretical calculation for two particles were accomplished, while people still push very hard to involve more realistic pictures.

However, in some experiments people did observe some enhancements, which may not due to the enhancement in the electric field.

A good example is the study of SERS on CO and N₂ ^[10]. It is found that the cross section of CO and N₂ are almost the same, while the SERS for these two molecules under the same conditions is of great difference. The enhancement of the former is about two orders of magnitude than the latter. Here chemistry must play a role ^[11].

Another example is a single molecule SERS experiment. It studied the correlation between the enhancement of Rayleigh scattering with SERS ^[12], and showed no strong connections. What's more it is found that the cross sections of the Stokes scattering and anti-Stokes scattering are not the same. This suggests there are some couplings between different vibrational states with the surroundings.

5.2. Single molecule SERS

One way to further study the relationship between them is the single molecule SERS. In the single molecule SERS what we observe is a single event rather than an average ensemble.

One of the earliest experiments were done by S. Nie and S. R. Emory ^[13]. They combined the SERS with the TEM and STM techniques, which enable them to study the relationship between the morphology of the particles and SERS effect. Here we show some interesting results from the experiment.

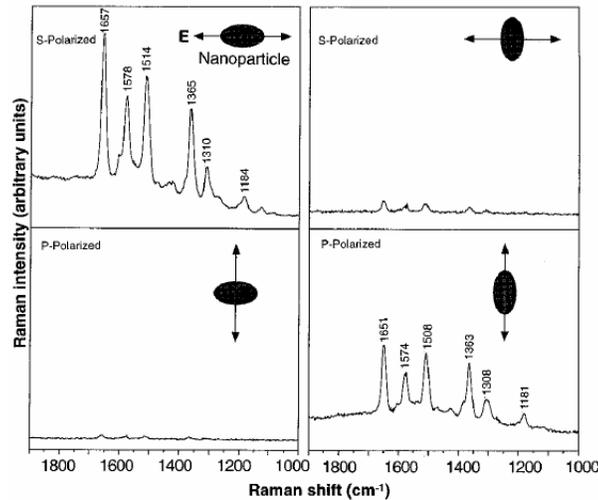


Figure 5. The polarization dependence of the SERS on single molecule

The paper collects some evidences to show this is the single molecule spectroscopy. One of the most important evidences is the polarization of the emitted light. The SERS signal for the bulk is depolarized, while figure 6 shows the intensity of SERS strongly depends on the polarization of the incident light, the orientation of the particles and the orientation of the molecules absorbed on the particles. By using polarization-scrambled laser excitation and detecting Raman emission with a dichroic polarizer, the orientation of the molecule can be determined.

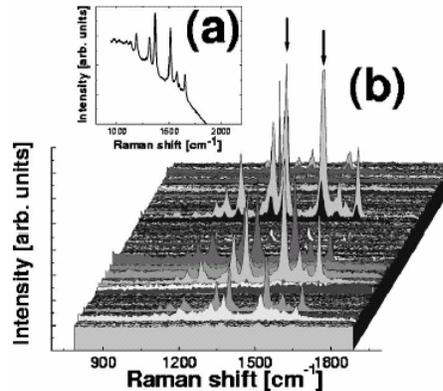


Figure 6. SERS spectrum for single particle at versus time ^[12]

It was also observed that the spectrum experienced a sudden change. It would completely disappear after a certain period of time as shown in figure 5. What's more, the spectra taken at different particles show some different characteristics, which suggest the difference in the local environment.

This experiment showed not all the molecules (or particles) were involved in the SERS effect, only a few of them display strong enhancement in signal. This is in accordance with the "hotspot" that people usually refer to. The study also showed there was no strong connection between the shapes of the particles with the enhancement. But they did observe that the size of the hotspot is about 3 times of average particle size. Which suggests that aggregation of the particles may play a role in the enhancement.

In another experiment, the narrow dispersed Au nano-particles were prepared^[14]. By studying the relationship between the size and the SERS effect, it was found the active size for Au is at about 60 nm, which is much smaller compared with the size of the active Ag particles (190~200 nm). What's more this is also in contradiction with the particle size calculated by the theory.

A paper studied the SERS of Hemoglobin adsorbed on the Ag particles^[15]. The interesting thing they found is that none of the "hotspot" consisted of an isolated single particles. All of them are dimmers or even more particles gathering together. This suggests that SERS for Hemoglobin is only possible for molecule situated between the two colloid particles.

Another interesting paper about single molecule SERS investigated the Stokes scattering and anti-Stokes scattering in the SERS^[12]. Their detailed study suggested that there would be a hidden resonance. And also they point out that physics only cannot give the whole picture of SERS, chemistry in some extent do play a role.

6. Application

As has been described above SERS is among the most sensitive techniques available to surface science. Its capability of delivering specific chemical identification and to couple this with a wide range of instruments, has led to its continuing use in both new and traditional areas of surface science. These are of prime importance to both fundamental research and to a range of industrial fields related to surface oxidation, adhesion, corrosion and catalytic processes and in advanced materials, biology and sensor research.

For those who are not familiar with SERS, it is essential to have a general feel about how to apply SERS for a specific purpose. Chowdhury *et al* used classical SERS system - silver colloids and provided rich information in their paper through the systematic SERS study on three interesting samples^[16]. After describing their experimental details, they demonstrated how to apply SERS to reveal in detail surface adsorption of organic molecules at colloids. Changing the solution pH and molecular concentration, one can analyze the relevant SERS spectra so as to identify protonated, deprotonated and hydrated states, and the orientation of the adsorbate as well as surface adsorption sites and surface coverage.

In the following part, the application of SERS in detection of DNA and RNA will be presented^[17]. Another paper engaged the novel Langmuir-Blodgett silver nanowire monolayers for molecular sensing by using SERS will also be introduced^[18].

6.1. DNA and RNA detection (summary of the literary) ^[17]

The procedure was shown in the figure 7. The straightforward idea of detecting DNA and RNA by SERS is to investigate the signals directly from the target. But this is not realistic, though SERS is called the fingerprint of the molecule. Even if we are able to take the Raman spectrum of DNA and RNA, it will be too difficult to analyze them with so many sequences inside one long chain. Here people come up with another smart idea by taking the advantage of a DNA chip. Hundreds and thousands of DNA and RNA with well-known sequences were placed on a single chip. Their positions were recorded in a computer database. The target DNA or RNA will only combine with the complimentary one on the chip. We can throw the target sequence onto the chip, and by locating where the target goes we can know the sequence of the target. SERS here provides us a way to identify the location.

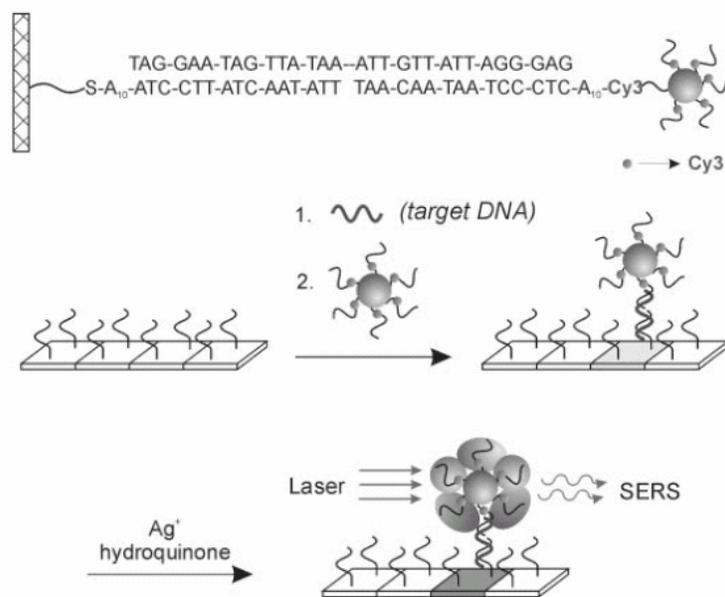


Figure 7. Scheme of the DNA and RNA detection by using SERS

The gold particles were designed in a special way to make use of the SERS. The dye Cy3 was attached to the gold particles and the target was attach to the Cy3 in the following procedure. This gold particle then was thrown onto the DNA chip. Next step is an essential step to obtain SERS, in which some silver particles were also added to the solution. And these silver particles will gather around the gold particles, which gives a SERS effect. Now we are in good shape to obtain the Raman signals from the target and locate it with high resolution.

But if we consider more carefully, the SERS technique here is just used to locate the target, which can also be achieved by Fluorescence and other techniques. One of reasons why people engage SERS here may due to its great sensitivity and enhancement fact.

6.2. Molecular sensing using SERS (summary of the literary) ^[18]

Not only nano-particles can give strong SERS effect, nano-wires can also provide good substrate for SERS.

Peidong Yang et al. used the traditional Langmuir-Blodgett to synthesize the aligned silver nanowire monolayer on the surface. The size of the nanowire is about ~50 nm in diameter and 2~3 μm in length. The interesting property of these nanowires is that the cross-sections are in the pentagonal shape and in the pyramidal tips. They are closed packed and are aligned parallel to each other. The resulting nanowire monolayers serve as excellent substrates for SERS with large electromagnetic field enhancement factors (2×10^5 for thiol and 2,4-dinitrotoluene, and 2×10^9 for Rhodamine 6G) and can readily be used in ultrasensitive, molecule-specific sensing utilizing vibrational signatures.

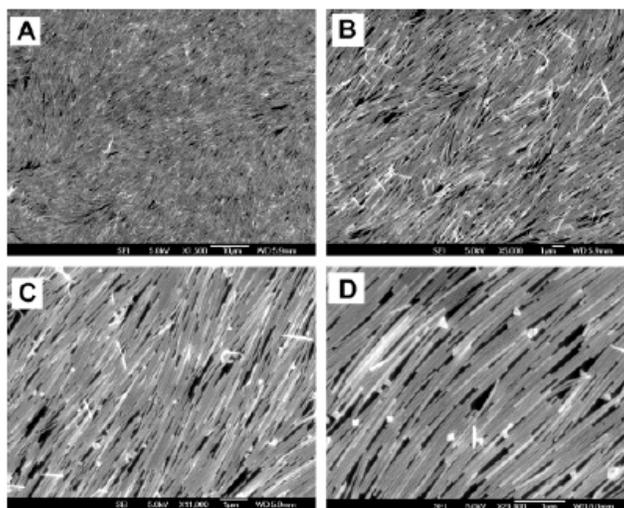
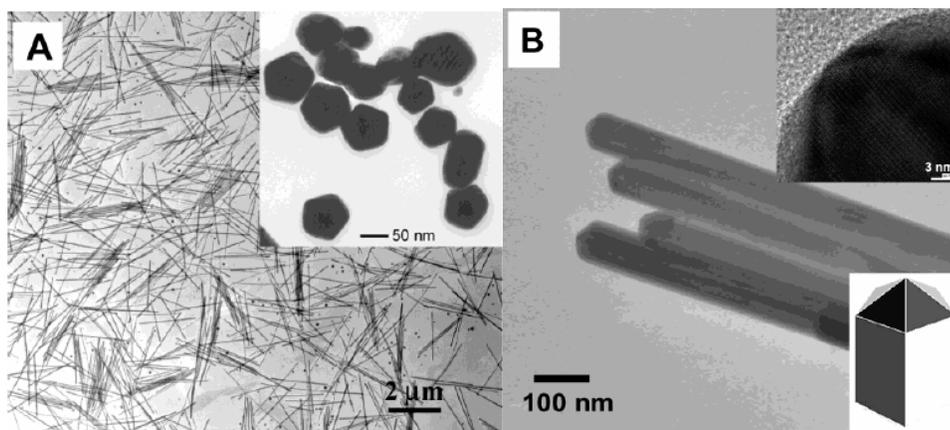


Figure 8. The nano-wires made as a SERS substrate

The special shape of the nanowires may play an important role in the SERS. What's more, the parallel alignment of the nanowires is another favor for the enhancement. This paper is a good example of combining the traditional method together with the advanced techniques.

Fantasies – Borrowing the SERS

Maybe it seems a little weird of trying to do SERS on the flat surface. It is well known that smooth surface is not SERS active. But still we want to do SERS on the flat surface. One of the good reasons is that we want to combine SERS with the Surface Force Apparatus (SFA). The traditional SFA can only measure the force applied onto the surface, this greatly limited the application of the technique. If we can combine SFA with advanced optical technique, the versatility of SFA will be greatly increased. The experiment on SFA requires two flat surfaces (little curved lens).

One intuitive idea is to make a 2-D pattern on the surface. This can be easily achieved when we made some modification to the 3-D pattern preparation [6]. But it is important for us to make the surface into a “sharp”-lattice or a lattice with fractal boundaries.

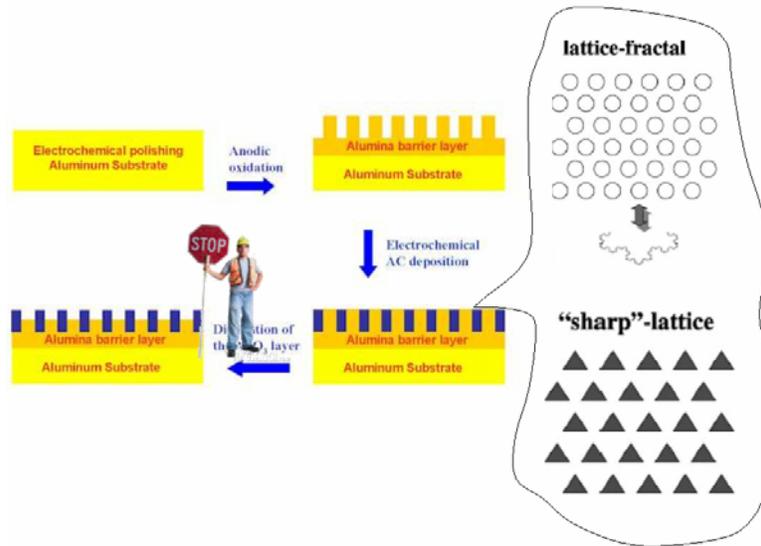


Figure 9. Possible way of making 2-D SERS substrate

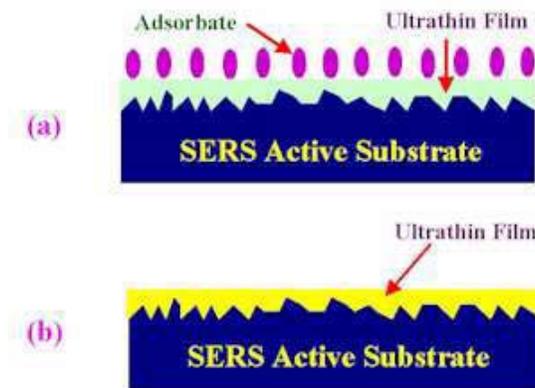


Figure 10. Doing SERS on a flat surface

Another way to do SERS on the surface comes from the fact that SERS does not require the direct contact the target molecules with the substrate ^[19]. It is SERS active within the few nanometers of the metal substrate. This enables two possible ways of making a flat SERS active surface. The first is shown in figure 10. It's like we are on the surface of a sea, under which there are mountains with different shapes. And this technique also shows SERS can be achieved without the chemistry contribution

One of the latest developments in SERS found that we could do SERS by simply putting an STM tip near the target molecules ^[20]. This gives us more freedom in doing SERS. Maybe we can attach some metal tips to the lens of the SFA setup to give the enhancement. However, it is very hard to manufacture such lens. What's more it requires the distance between the tips and the contact area is no more than few nanometers, which is very demanding in experimental skills.

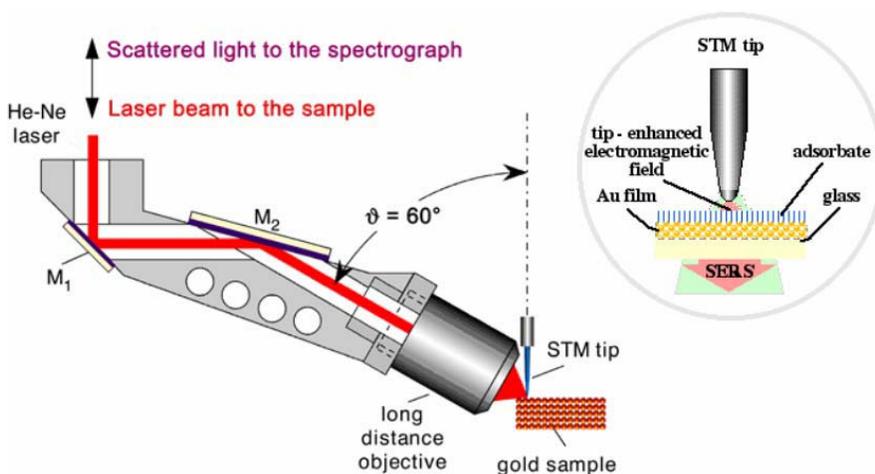


Figure 11. Doing SERS by using STM tip

There are still difficulties in understanding SERS and combining it to other techniques. A current goal in theory is to quantify the SERS effect. Now we know both physics and chemistry play a role in the enhancement, however we are still no sure in what exact amount? The description of “hotspot” apparently cannot fulfill this demand. On the other hand, people push this technique to a wide range of research work. Together with other techniques, SERS even provides a promising way of study the single molecule spectroscopy. This is not only a powerful spectroscopic tool, but also shines light on the mechanism of SERS.

Homework

I also gave a literature review about SERS in the group seminar. People kept on raising their hand for questions. Some of the questions inspired me and helped me refine this paper. I listed them here, which may assist you better understand the paper. The questions I did not answer are your homework. You can try to solve them or find the answer in my paper.

- 1. What's the difference between the Resonant Raman and the Fluorescence, it seems there is no difference in the energy diagram. Where is the enhancement of resonant Raman come from?**

I did not mention the resonant Raman in my paper. It is simply the case when the virtual excited state coincides with the electronic energy state. Think about it! Why this can boost up the Raman signal?

- 2. How to determine the polarization of SERS?**

This seems to be a basic question for the introduction of optics, which is not easy to answer.

- 3. Do we observe the enhancement on single particles or only when the particles gather together?**

The results of experiment vary. Some observed enhancement on single particle, some only observed SERS in the spot when two or more particles gathering together.

- 4. What's the evidence for the single molecule SERS, why they are blinking on and off?**

Find the answer in my paper. Why they are blinking on and off? First I thought it was the particles diffuse in and out the focal region, but in most single molecule SERS experiment, the target was fixed on the static surface. So why do they blink?

- 5. Does SERS require the direct contact of the target molecules with the substrate?**

Find the answer yourself.

- 6. Can you come up with some other ideas of doing SERS on the flat surface?**

If you really think you have some smart ideas on this. Please write me an Email. Or you can try to do experiment by yourself and it should be a nice paper.

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