

Recent Progress in SERS-Based Anti-counterfeit Labels

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Anti-counterfeit labels protect many commercial goods, drugs, and currencies from counterfeiting activities. Recently, the designs of anti-counterfeit labels have emerged utilizing surface-enhanced Raman scattering (SERS) as a powerful technique, in which SERS-active materials provide strong Raman signals of probe molecules. These signals are unique and, so far, have rarely been used in practical anti-counterfeit labels applications. In this review, the general methodology of using Raman and SERS in designing anti-counterfeit labels is first introduced. Then, two types of secret information in SERS labels, spectroscopic information and graphical information, are detailed and discussed with a focus on how the molecular information is encoded with SERS labels. Later, several advanced SERS labels are presented which combine existing security features such as barcode, quick response code, fluorescence, and unclonable features. Finally, the challenges in building usable SERS anti-counterfeit labels are discussed and possible research directions are described.

counterfeiting products from authentic ones. Several labels have been developed and used in our daily lives, such as watermarks, color-shift inks, and 3D security ribbons in 100 US-dollar bills. Meanwhile, the packaging of pharmaceutical products may contain several types of overt features (barcode, holography, etc.) or covert features (radio-frequency identification tags, biometrics, etc.) that are hard to be duplicated.^[5] These anti-counterfeit labels helped us discover counterfeiting products and deter future counterfeiting activities. Counterfeiters, however, continue to develop new methods for defeating the anti-counterfeit labels, so the continuous updates of these labels are crucial.

To design an anti-counterfeit label, the most important part is storing security information, which could be a unique structural design or a material with unique

1. Introduction

Counterfeiting activities have become a significant economic problem throughout the world. According to a report by the Organization for Economic Cooperation and Development, in 2016, counterfeiting merchandise trade took over 3.3% of the total amount of world trade.^[1] Also, based on the Global Brand Counterfeit Report, the amount of global counterfeit had reached 1.2 trillion US dollars in 2017 and would be bound to 1.82 trillion in 2020.^[2] Counterfeiting activities are not only damaging to the global economy but also harmful to societal wellbeing. For example, counterfeit banknotes damage the stability of the markets and the reputation of governments. Counterfeiting pharmaceuticals have caused harm to human health or even caused death in some instances.^[3] Therefore, it is essential to take action in fighting counterfeiting activities. Such action could be setting up warning signals, allocating budgets for anti-counterfeiting, and deterring counterfeiting activities on the supplier or consumer side.^[4] The most crucial part is to deter counterfeiting activities, and an effective approach is utilizing anti-counterfeit labels to help differentiate

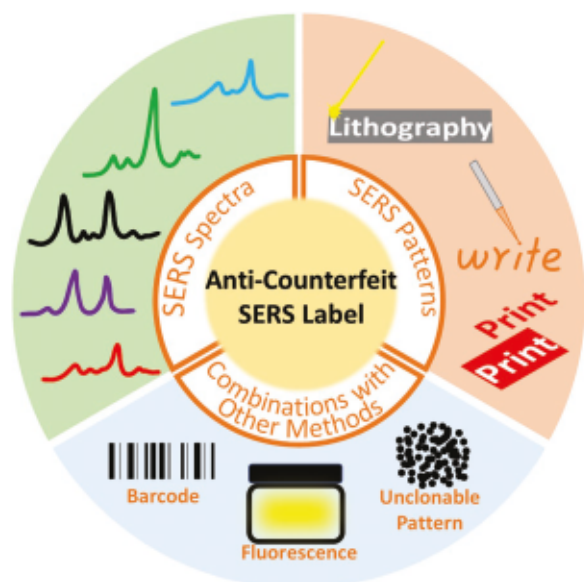
optical properties. For example, Han and co-workers recently introduced a new structural design.^[6] They produced QR-code-shape micro taggants which could encode a large amount of information. This QR-code could authenticate drugs as well as the possibility of track-and-trace. Designated patterns can be produced using laser patterning,^[7–9] printing,^[10–12] assisted self-assembly,^[13] and microfluid.^[14] Meanwhile, random patterns were also fabricated to build robust anti-counterfeit labels.^[15] Some anti-counterfeit labels will require unique recognition methods, such as a particular viewing direction for a hologram^[16] or a spectroscopic measurement for fluorescent ink.^[17] Recently, researchers have achieved several advancements in the design of unique patterns and the introduction of a novel recognition approach in anti-counterfeit labels. For example, micro-scale patterns^[6] and unclonable patterns^[18,19] have enhanced the security of structural designs. Various functional materials have been integrated into anti-counterfeit labels to bring novel recognition methods and hide secret information, such as upconversion nanomaterials, which emit light at a shorter wavelength when excited by a longer wavelength light.^[11,20,21]

In recent decades, several reports have focused on using Raman scattering in anti-counterfeit labels.^[7,22–35] Since Raman scattering is a spectroscopic technique that is rarely used commercially today in the field of anti-counterfeit labels, these new labels with unique Raman scatterings have a higher security level and are suitable as next-generation anti-counterfeit labels. In this review, we will focus on the development of anti-counterfeit labels based on surface-enhanced Raman scattering (SERS), which includes the uses of SERS spectra, SERS patterning, as well as its combination with other techniques (Scheme 1).

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Scheme 1. An overlook of SERS-based anti-counterfeit labels.

2. Raman for Anti-counterfeit

Raman scattering, first discovered in the 1920s,^[36] refers to the inelastic scattering of photons as they interact with molecules. The energy difference between the incident photon to the scattered photon is associated with the energy of the molecular vibrational states. Raman spectroscopy is a characterization method that reports Raman spectra of samples, in which Raman scattering intensities of a molecule at different Raman shifts are presented to reveal the unique vibration information of a molecule. Besides anti-counterfeiting, Raman scattering has wide applications in many fields, such as sensing,^[37–40] imaging,^[41–43] and diagnosis.^[44–46] The application of Raman scattering in anti-counterfeit can be classified into two fields, direct identification of counterfeiting products and anti-counterfeit labels based on Raman scattering.

2.1. Direct Identification of Counterfeiting Products

Nowadays, people often need to distinguish counterfeit products from genuine ones for drugs,^[47,48] paints,^[49] and banknotes.^[50,51] Raman spectroscopy is a noninvasive analytic method with high sensitivity and accuracy, thus often used in forensic identification.^[49,52] For example, Clark, as well as other scientists, has promoted the use of Raman spectroscopy in the pigment analysis,^[53–55] and such dye-analysis ability allows Raman to be used in the identification of counterfeit inks,^[56] paints,^[57,58] artworks,^[59,60] and banknotes.^[50,51,61,62] Poppi and co-authors applied Raman spectroscopy to discriminate authentic R\$50 banknotes to counterfeits (Figure 1).^[51] They found that the characteristic Raman peaks of the ink used in LaserJet printers or Inkjet printers are not identical to those obtained from authentic banknotes. For example, the chalcographic ink on “counterfeit” banknotes showed strong Raman peaks attributed to phthalocyanine pigment, while the Raman spectrum of authentic chalcographic ink revealed the existence

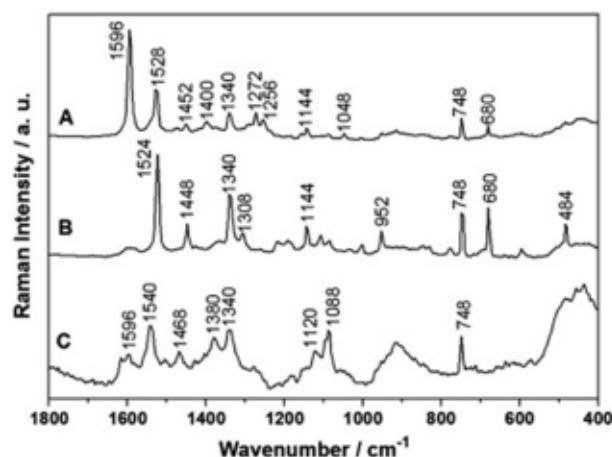


Figure 1. The Raman spectra of the ink from a) genuine banknotes, b) laserjet-printed banknote, and c) inkjet-printed banknote. Reproduced with permission.^[51] Copyright 2013, Elsevier.

of both phthalocyanine and diarylide pigments. The authors used two pattern-recognition methods, principal component analysis (PCA) and partial least squares for discriminant analysis (PLS-DA), to process their Raman spectra for high accuracy and reliability.

Besides banknote analyses, Raman spectroscopy was also applied to detect counterfeiting drugs. For example, Matousek and Eliasson demonstrated the usage of a novel spatially offset Raman spectroscopy (SORS) to identify counterfeiting drugs.^[63] Compared to conventional methods, SORS could probe the deeper layers of samples, effectively suppressing interferences from tablet coatings or capsule shells to reach the active drug ingredients. Using this method, the researchers successfully identified various commercial drugs with higher accuracy than conventional Raman spectroscopy.

2.2. Anti-counterfeit Labels based on Raman Scattering

The direct identification of a counterfeiting product always requires the existence of “indicator” molecules such as dyes in paints or ingredients in drugs. However, these types of molecules can be limited. Raman anti-counterfeit labels, on the other hand, can introduce new types of molecules as “indicators” to differentiate similar products or create personalized profiles for specific products. Therefore, for Raman-based anti-counterfeit labels (Raman labels), the two crucial parts would be the types of secret information and the capacity of that information.

2.2.1. Types of Secret Information

In a typical Raman label, secret information can be types of molecules, amount of molecule, and arrangement of molecules. First, various Raman probe molecules (sometimes called reporters) will give different peak positions and intensities in a Raman spectrum due to their unique vibrational states associated with molecular structures. Second, when the laser

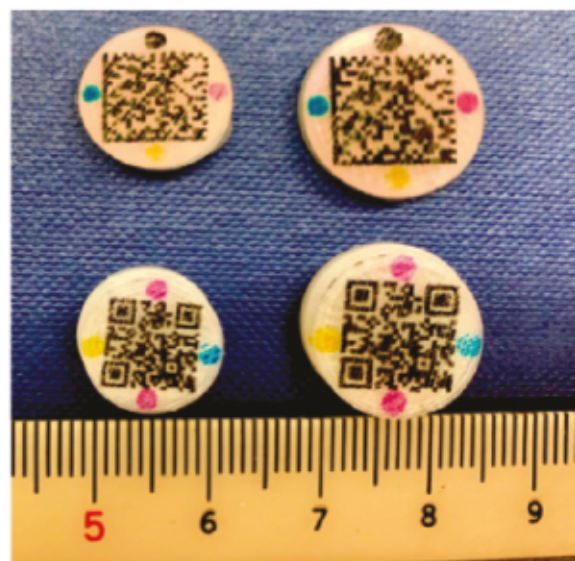


Figure 2. 3D printed tablets with novel anti-counterfeit designs; a) data matrices with model material inks and b) QR codes with model material inks. Scale bar is in cm. Reproduced with permission.^[65] Copyright 2019, Elsevier.

wavelength and intensity are fixed, varying the number of molecules will change the peak intensity. Different chemicals can further be mixed to vary the peak intensity ratio in the spectra. Third, the spatial arrangement of molecules will result in different spectra at each pixel. Combining these pixels, a pattern can be constructed with unique Raman spectra, which can be revealed at a particular laser excitation and with other specific experimental parameters such as laser polarization. In addition to these three typical anti-counterfeiting features, Raman-based anti-counterfeit labels can also be combined with other security techniques such as color-shift inks or coded patterns to make even more sophisticated security labels.

A design of tablets with Raman-based anti-counterfeiting features was illustrated by Basit and his co-workers.^[35] Aiming to produce labels for personalized pharmaceuticals, the authors printed 3D tablets with QR codes and used 2D inkjet printing to add four dots containing Raman-active inks (Figure 2). The QR codes were used to track and trace the processing of the tablet, and the four ink dots further enhanced its security. These Raman-active inks are Eudragit RS100 ink, methylparaben 20 ink, Eudragit RS100 ink, and sodium benzoate. By measuring the Raman spectra at those positions, the Raman peaks were recognized, which led to the identification of the ink materials. Here, the types of inks and their locations are the novel identity for the Raman-active labels on tablets. This novel approach provided safer protection for healthcare workers and patients when distributing or using these drugs.

2.2.2. Information Capacity

Anti-counterfeit labels based on Raman scattering contain various information, which is introduced by the Raman probe molecules. In general, the two main types of security

information are spatial information and spectral information. Spatial information is linked to the locations of Raman-active probe molecules in the labels, while the spectral information is connected to the types and the amount of the Raman probe molecules. The spatial information could be represented by the number of pixels (p), where each pixel has an individual Raman spectrum. The spectral information could then be varied by the number of molecule types (m), and the number of amount variables (n). As such, the number of molecular combinations at each pixel can be represented by n^m . Therefore, we can derive a representation of encoding capacity (C)

$$C = n^{mp} \quad (1)$$

For example, in a 10 by 10 label with two choices of Raman-active probe molecules, and each type of molecule has three differentiable concentration variables, the possible molecular combination is 3^2 , and the encoding capacity is 9^{100} or about 10^{95} . This equation is ideal, while in actual cases, a researcher needs to consider the error that could occur when differentiating the spectra of two kinds of molecular combinations or from two pixels. Generally, high information capacity is preferred in Raman labels because the labels with more variations are harder to forge and have a higher tolerance to errors.

Furthermore, the unique information in a Raman label can also be coded to represent text information. For example, Gao et al. built a super capacity coding system by utilizing the Raman spectra of different molecules (Figure 3).^[64] In their work, each molecule was covalently bonded to polymer beads. Unique Raman spectra were obtained by varying the types of Raman probe molecules, which were represented by upper-case characters, A, A', B, B', etc. Different intensity levels of a peak resulted from molecule amount, which was represented by numbers of characters, 0, 1, 2, 3, etc. These two parameters were used to represent different beads. Then, each bead could be assigned to an ASCII (American Standard Code for Information Interchange) code, which can be successfully converted to text messages from the spectroscopic information in these labels. This coding system with high information capacity is suitable for data storage and anti-counterfeiting applications.

3. SERS-Based Anti-counterfeit Labels

3.1. Overview

SERS is an advanced technique that is built upon the study of Raman scattering. In the 1970s, scientists discovered that Raman signals of pyridine molecules were enormously increased on a rough silver surface.^[65] Beyond silver, researchers have also discovered a series of plasmonic materials, on the surface of which, Raman signals of probe molecules are strongly enhanced. These plasmonic nanomaterials are used as SERS-active substrates, containing SERS "hot spots," such as sharp corners or coupled structures. Probe molecules adsorbed in these "hot spots" will have enormous enhancements of their Raman signals. The recorded enhancement factor (EF) of a Raman signal has been raised to 10^{14} with a well-designed SERS substrate.^[66,67] With strong Raman

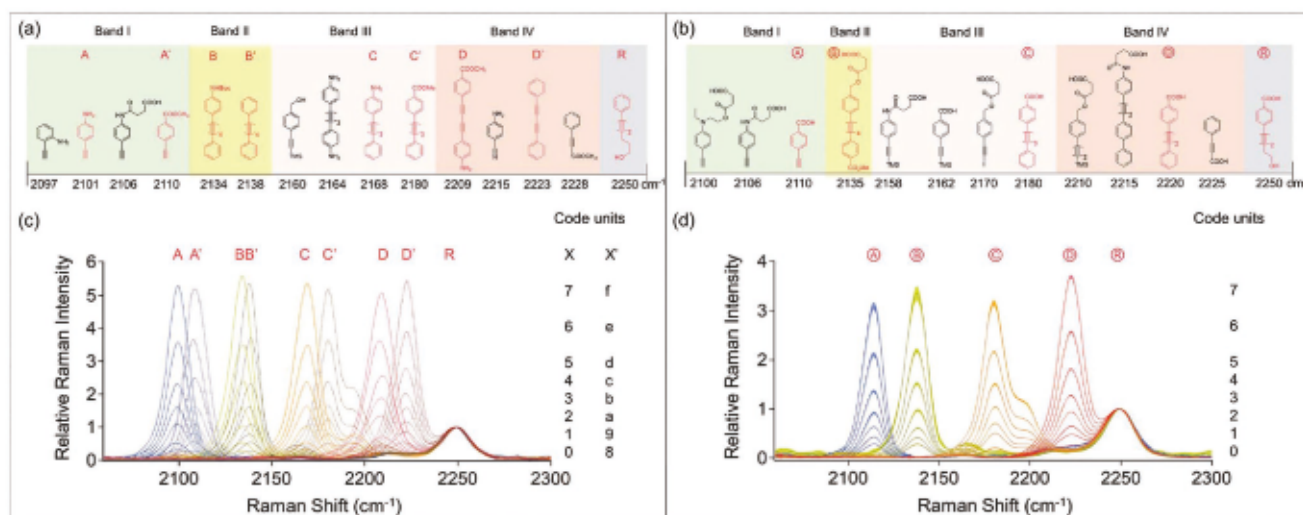


Figure 3. a,b) The alkyne selection and c,d) the corresponding spectral information of the super-capacity coding system. Reproduced with permission.^[64] Copyright 2020, Royal Society of Chemistry.

signals, SERS has been widely applied in various fields such as chemical and biological sensing,^[68–71] medical technology,^[72–74] forensics,^[49,75] and labeling.^[76–78] SERS techniques have demonstrated outstanding potential in the development of advanced anti-counterfeit labels.

SERS-based anti-counterfeit labels (SERS labels) have several advantages. First, compared to fluorescence signals, SERS peaks are usually much narrower, enhancing the spectral resolution and increasing their information capacity. Second, a variety of chemicals can be used as SERS probe molecules to provide unique molecular fingerprints, and these chemicals can be combined to generate new kinds of fingerprints that cannot be easily reversely engineered by counterfeiters. This results in more complex labels. Third, SERS labels can be used together with other anti-counterfeiting techniques, e.g., fluorescence, to achieve an even higher level of security. Fourth, SERS labels could be patterned on a large scale, which will facilitate their commercialization. Fifth, SERS is a relatively new method that is less known to counterfeiters. Overall, SERS-based anti-counterfeit labels would be extremely hard to reversely engineer, and SERS is a unique technique that can be potentially used to develop efficient, secure, and flexible anti-counterfeit labels. In the following sections, we will discuss the fabrication of SERS labels, the encoding of secret information using SERS spectra and SERS patterns, and the combination of SERS with other methods for anti-counterfeiting applications.

3.2. Fabrication of SERS Labels

Various methods have been developed to fabricate SERS labels,^[7,22–31,79] such as lithography, molecular adsorption, etc. In many cases, the design of SERS labels is defined by the fabrication approaches, which in turn will impact the anti-counterfeiting performance. A common ground of these various approaches is to attach Raman probe molecules onto presynthesized SERS substrate of plasmonic materials.

3.2.1. Fabrication of SERS Substrates

To fabricate a SERS-active substrate, choosing the type of plasmonic materials is important. There are plenty of plasmonic materials that have been used as SERS substrates, such as noble metals,^[80–82] nonprecious metals,^[82–85] semiconductors,^[83,86] and graphene.^[87–89] Typically, SERS labels only use a few types of plasmonic materials, including gold, silver, and aluminum. Gold and silver are the two most popular SERS substrates with giant physical enhancements, which are primarily used in the SERS-based anti-counterfeit labels. In most cases, the cost of gold or silver materials in these SERS substrates is relatively trivial as compared to their overall expense. Nevertheless, some researchers developed aluminum structures as SERS-active substrates in the field of anti-counterfeit due to the high abundance of aluminum.^[30]

Recently, nanoscale plasmonic materials have been widely used as SERS substrates because the plasmonic coupling in nanomaterials can provide high SERS enhancement. As a result, all the recent publications involving SERS anti-counterfeit labels have used plasmonic nanomaterials as SERS substrates. The morphology of these nanomaterials varied greatly and includes nanosphere, nanostar, nanowire, nanopillar, nanoisland, aggregate, and metafilm.^[22,24,27–28,32,90] The plasmonic coupling in these materials is quite different and results in their varied enhancement factors. Overall, nanoparticles with a roughened surface have demonstrated strong SERS signals with a higher enhancement factor than those with a smooth surface. For example, as shown in Figure 4, Jiang group recently reported a type of SERS-based security ink using gold nanostars as SERS substrates.^[33,91] The rough surface of nanostars provided strong SERS enhancement, which could identify a small number of molecules with PCA. The high SERS signal makes it suitable to develop security inks with a high information capacity.

There are generally two ways to synthesize SERS-active substrates in fabricating SERS labels. The first way is to form a thin layer of metal film on a predesigned nanostructure.^[7,22,26]

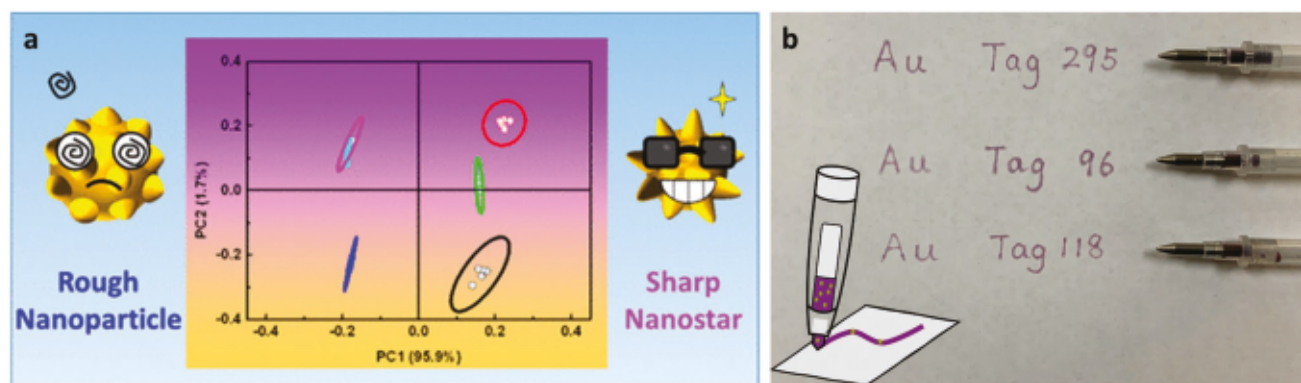


Figure 4. a) Principal component analysis demonstrates nanostars' higher sensitivity with sharp branches. Reproduced with permission.^[91] Copyright 2020, American Chemical Society. b) SERS security inks developed with gold nanostars, which were used for written anti-counterfeit labels. Reproduced with permission.^[33] Copyright 2021, Royal Society of Chemistry.

These predefined nanostructures could be self-assembled polymeric nanoparticles or lithographically fabricated arrays of polymeric nanowires or nanopillars. It is suitable to produce nanostructures with good long-range ordering, which results in SERS labels with high uniformity. The other way is to synthesize gold or silver nanoparticles via wet chemistry.^[23,24,31,90] Then, these nanoparticles were deposited or self-assembled to form a label. This method can have good control of the morphology of nanostructures. In addition, the colloidal nanoparticle solution is rather easy for material processing during the label fabrication process. The challenge of this method is the quality control of the deposition or self-assembly step.

3.2.2. Attachment of Raman Probe Molecules

Besides the SERS substrate, Raman reporter is another crucial component in the SERS labels since the basis of SERS coding is diversifying SERS spectra of those probe molecules. However, the use of Raman reporters in the SERS labels could be different from that of the Raman labels. On the one hand, SERS substrates in SERS labels provide much stronger Raman signals than general Raman, which dramatically improves the probe molecules' usage efficiency and probably also increases the difficulty in the reverse-engineering process. On the other hand, SERS enhancement requires the Raman reporters to be very close to the SERS substrates, in which the molecules need to be attached to the SERS substrate via either chemical interactions or electrostatic interactions.

Two types of Raman probe molecules are typically used in SERS labels. The first type is molecules with thiol functional groups because thiol has a strong reaction with gold and silver, the most common SERS substrate. The other type of Raman reporters will have a strong electrostatic force with the surface charge of plasmonic substrates, where the surface charges are the results of the capping agents that are existed on the surface of SERS substrates. This interaction usually happens between the dye ions and the SERS substrates. Overall, dyes and thiolated molecules are the two most used Raman reporters in SERS labels.^[22,25]

In the fabrication of SERS labels, the methods used for Raman reporter attachment play an essential role in the distribution of these Raman reporters, which, consequently, will affect the spectral outcome and the spatial resolution. The SERS probe and substrate can directly interact via drop-casting probe solution on a bulk piece of the substrate or by mixing colloidal nanoparticle solution with SERS reporters. However, these methods usually lack of sufficient control. First, the uncontrolled distribution of molecules will lower the flexibility of SERS patterning, while in many cases, such controlled patterning of molecules could be a unique anti-counterfeiting feature (see discussion below). One of the solutions was introduced by Cui et al., where they used a lithographic method to design nanoscale polymer masks and successfully controlled the spatial distribution of probes on substrates.^[7] Second, multiple Raman reporters could either react with each other or have a competitive relationship when adsorbing on the surface plasmonic colloids. A feasible solution is using core-shell nanoparticles with single-type molecule embedded, which was introduced by Gu et al.^[31] and Feng et al.^[92] In their work, the chemical reaction and competitive adsorption between different Raman reporters are effectively blocked.

3.3. SERS Spectra for Anti-counterfeiting Applications

An SERS spectrum tells the response of probe molecules inside an SERS anti-counterfeit label to the external laser excitation. The spectral information will be used to reveal the major secret feature of the SERS label. Such secret information is typically controlled in three manners: the types of molecules, the types of substrates, and the multiplex of spectra.

3.3.1. Impact of Raman Probe Molecules

The most direct way to control the outcome of a SERS spectrum is by utilizing various Raman reporters. Since each molecule gives a unique Raman spectrum, decrypting the SERS labels will be extremely difficult unless the identifications of molecules are figured out. Many different types of probe molecules

Table 1. Table of probe molecules used for SERS anti-counterfeit labels and the corresponding Raman band.

Molecule	Band [cm^{-1}]	Ref.
2-Naphthalenethiol (2-NT)	1068, 1381, 1580, 1621	[22,28,31]
4-Methylbenzenethiol (4-MBT)	1079	[7,22,29,31]
Polydiacetylene (PDA)	2100	[93]
Rhodamine B isothiocyanate (RhBITC)	1200	[7]
4,4'-Bipyridine (4-bpy)	995, 1200, 1270, 1580	[23]
4-Aminothiophenol (4-ATP)	1078, 1040, 1578	[24,25,28,79]
Crystal violet (CV)	1617	[25,26]
Rhodamine B (RB)	1649	[25,26]
Malachite green (MG)	1394, 1617	[25,26]
4-Chlorothiophenol (4-CTP)	336, 536	[79]
4-Mercaptophenol (4-HTP)	390	[79]
4-Nitrophenol (4-NTP)	1340	[31,79]
4-Methoxy- α -toluenethiol (MATT)	665, 729	[79]
5,5'-Dithiobis(2-nitrobenzoic acid) (DTNB)	1147	[79]
3,5-Bis(trifluoromethyl)benzenethiol (3-FMBT)	814, 1000	[79]
Rhodamine 6G (R6G)	622	[27]
Eosin Y (EY)	1639	[27]
Naphthalene (NAP)	1090, 1330, 1590	[30]
Triethoxyphenylsilane (TEPS)	1090, 1330, 1700	[30]

can be used to fill in the role of Raman reporter, as has been discussed in the previous section of label fabrication. The researcher can specify a particular Raman band as the target in the SERS label for authentication. In **Table 1**, typical SERS reporters and the Raman bands used in anti-counterfeit labels are listed. These unique Raman bands are easily distinguishable in the spectra and can be located at multiple positions in the labels. For example, Cui et al. used 4-methylbenzenethiol (4-MBT) as their Raman reporter.^[22] 4-MBT has an easily distinguishable Raman band at 1079 cm^{-1} , which was monitored to provide judgment of label versus no label. Multiple Raman bands from the same reporter could be used as well. For instance, Fukuoka et al. constructed SERS active gold nanoparticles with 4,4'-bipyridine (4-bpy) as the Raman reporter.^[23] In their study, the Raman peaks of 4-bpy at 995, 1200, 1270, and 1580 cm^{-1} were used for detection. Their results demonstrated that these four Raman bands of 4-bpy have extremely strong intensities with the SERS labels on the drugs compared to the unlabeled drugs.

3.3.2. Impact of SERS Substrates

It is worth noting that the type of Raman probe molecules is not the only parameter in determining the outcome of the SERS spectra. The sizes and shapes of nanoparticles can also play a major role, not only in the overall intensities of the SERS spectra but also in the relative intensity ratios for various Raman bands. As of today, researchers can effectively fabricate a wide range of shape-dependent plasmonic nanoparticles such as nanorods, nanospheres, and nanostars. These nanoparticles

will have their unique plasmonic resonance ranging from visible to near-infrared regions, which will impact the SERS spectra that are excitation wavelength dependent. Furthermore, each type of uniquely shaped nanoparticles could be used as a building block for more complex nanoscale architectures. For example, Si et al. demonstrated the potential of using plasmonic nanoparticles as building blocks for SERS anti-counterfeit labels (**Figure 5**).^[24] Spheres, rhombic dodecahedral, and star-shaped nanoparticles were used. Each variation of nanoparticles gives a different SERS spectrum and a different enhancement factor. The authors successfully constructed nanosheets using different shapes and sizes of building blocks and then developed SERS barcodes for anti-counterfeiting applications at a specific wavelength. This work demonstrated that the mix and match of the building blocks could result in almost endless combinations of SERS labels, making them impossible to be decrypted.

3.3.3. Spectra Multiplexing

In addition to using a single type of probe molecule for SERS labels, multiple Raman reporters can be combined, working together to form even complex SERS spectra.^[94–96] Overlapping various simple spectra creates a more complex spectrum, which can increase a label's intricacy dramatically. For example, Li et al. combined multiple SERS probes to produce an encoded magnetic composite of microspheres for anti-counterfeiting applications (**Figure 6**).^[79] In their SERS labels, they combined up to four types of Raman reporters and obtained much more complex SERS spectra. These complex spectra were further

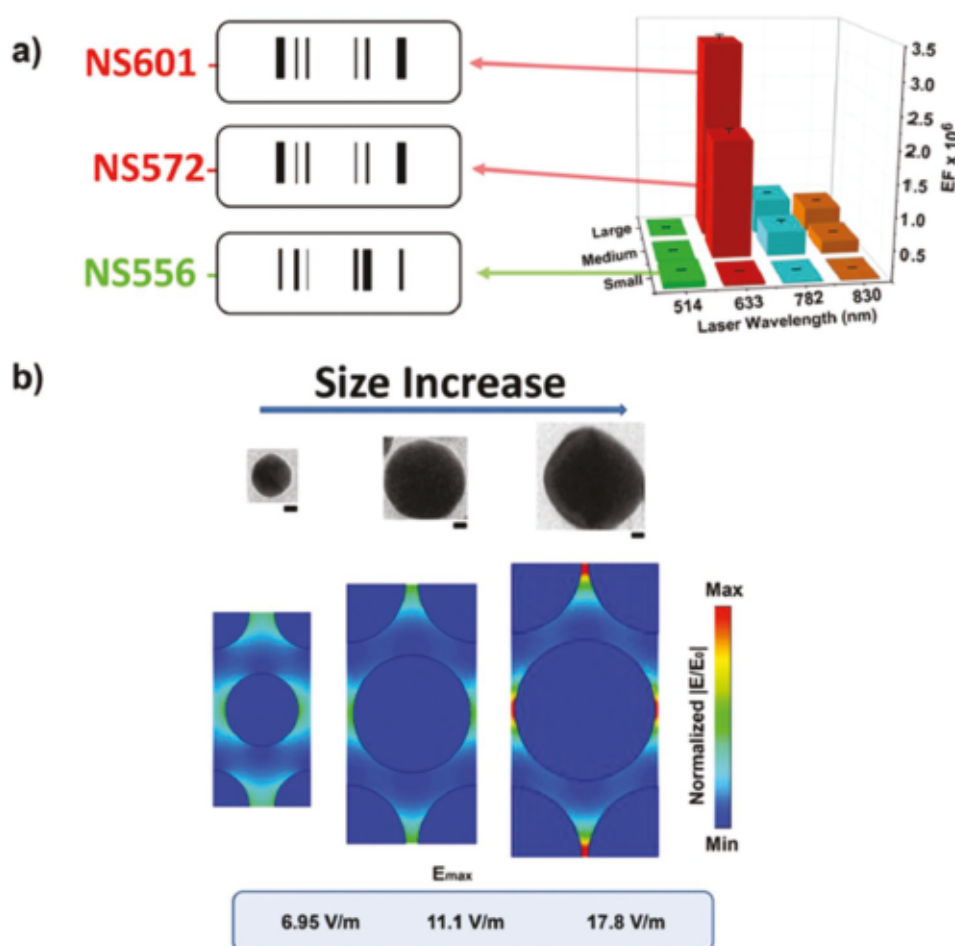


Figure 5. a) SERS code using different sizes of gold nanospheres. The EF values of three sizes of nanospheres under different excitation wavelengths are compared. b) Simulation of the electric field of three sizes of nanospheres under 633 nm excitation. Scale bar 10 nm. Reproduced with permission.^[24] Copyright 2015, Wiley-VCH.

combined with fluorescence spectra to provide a dual-mode encoding system with an even higher security level for anti-counterfeiting applications.

Using an even more significant number of Raman reporters has resulted in more complicated SERS labels. For example, Gu et al. recently demonstrated an anti-counterfeit label utilizing ten different molecules (Figure 7).^[31] In their study, gap-enhanced Raman tags (GERTs) were synthesized with only one type of molecule inside each tag. The ten Raman reporters were used to fabricate ten unique types of GERTs with strong SERS signals. These GERTs are then randomly distributed on the substrate to form a 2D pattern that is impossible to replicate. To “read” these Raman labels, a spectrum-demultiplexing method was applied. The results showed that although the ten GERTs have overlapping peaks in the range of 802–1600 cm⁻¹, the weight of every single spectrum can be determined by optimizing a best-fit spectrum, in which the best-fit spectrum has the least difference with the measured data. The authors further demonstrated that the complex spectrum could be converted to either a 2D or a 3D plot by using binary encoding and quaternary encoding. The readout speed for these SERS labels has been very promising.

3.4. SERS Patterning for Anti-counterfeit Labels

SERS patterning is a process to form 2D images which were constructed by extracting certain information (such as peak intensity and its ratio, peak position, and peak width) in an array of SERS spectra across an area of the sample. The use of SERS patterning has gathered significant interest in anti-counterfeiting applications. Scientists have created unique SERS patterns that utilize the Raman reporters in the SERS labels over an area ranging from nanometer to centimeter-scale.^[22,27,97] In this section, we will present some examples of anti-counterfeit labels with macro- or microscale SERS patterns, and show how researchers utilized many of their unique features for anti-counterfeiting applications.

3.4.1. SERS Patterning with Materials at Different Scales

Macro- and microscale structures used in SERS labels can be generally differentiated with naked eyes, which avoids the necessity of a microscope. For example, Ying et al. fabricated macroscale, large-area, flexible-patterned plasmonic

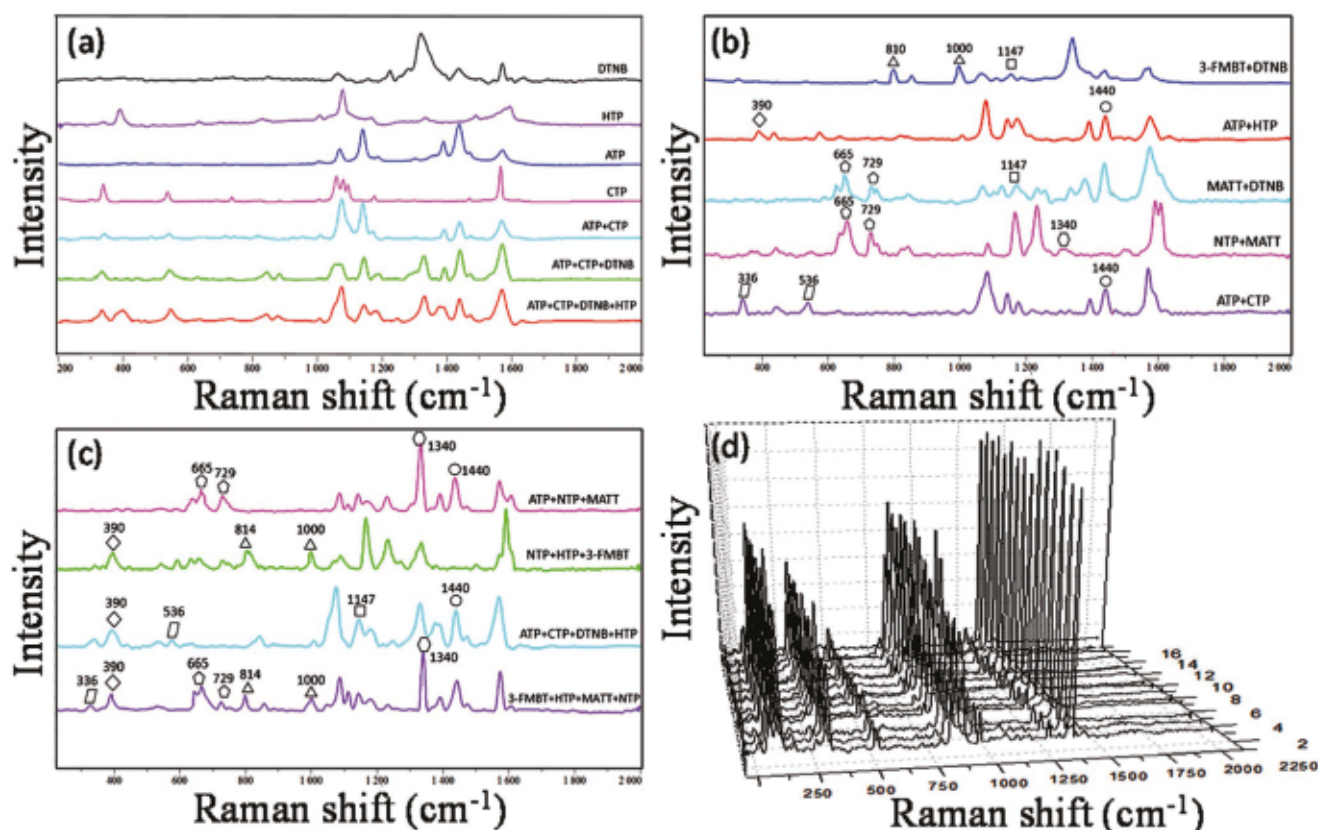


Figure 6. Raman spectra of the FMF/MNP/Ag-NPs/SiO₂ microsphere immobilized with a) different kinds of Raman probes, b) two kinds of Raman probes, and c) three and four kinds of Raman probes; d) Raman spectra of the isolated, immobilized microsphere randomly chosen from 15 areas. Reproduced with permission.^[79] Copyright 2016, American Chemical Society.

metasurfaces (FPPMs) and demonstrated the capability of using SERS patterning in anti-counterfeiting applications.^[26] These FPPMs were created by designing laser engraving patterns into monolayers of self-assembled polystyrene beads. The patterned beads were then taken up by Scotch tape and subsequently covered with a silver film. This approach allowed for patterns as large as 6 cm × 4 cm with structure resolution higher than 100 μm. In their experiment, an FPPM plasmonic butterfly structure was treated with rhodamine B, where it was

revealed not only to be SERS active but also tunable by varying the size of the polystyrene beads or by changing silver film thickness. Anti-counterfeiting applications using their FPPM materials were accomplished by creating a complex 5 × 5 array layered with three types of organic dyes. With the selective placement of these dyes over the array, the authors demonstrated successful encryption of the initials of the author's institution (ZJU) in the SERS labels. Such information would not be available unless a reconstruction process of the obtained

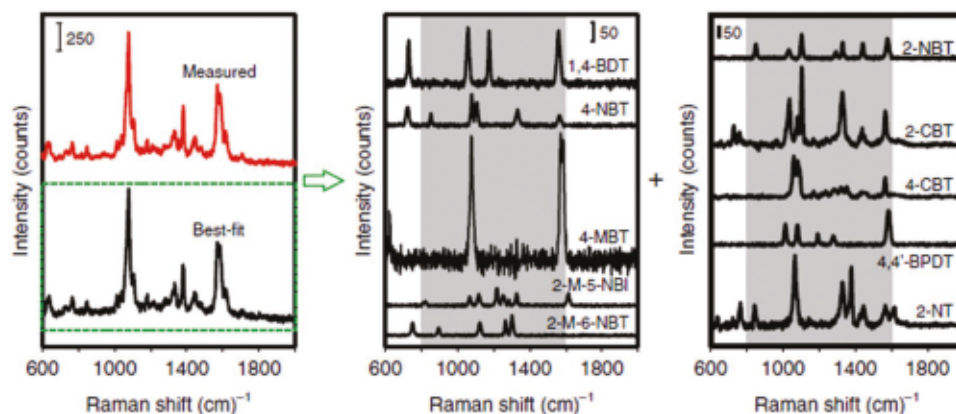


Figure 7. Spectral demultiplexing to quantify the abundance of ten types of GERTs. Reproduced under terms of the CC-BY 4.0 license.^[31] Copyright 2020, The Authors, published by Springer Nature.

SERS spectra was conducted using a classical least squares fitting algorithm. Similarly, that group also reported a study of using the FPPMs to fabricate multidimensional SERS barcodes for anti-counterfeiting applications.

Micro/nanoscale materials have also been studied for SERS imaging in anti-counterfeiting applications. As we know, nanostructures are highly attractive for SERS imaging as they could be excellent substrates that can have intensive enhancement of local electromagnetic fields, which will then lead to strong SERS signals. For example, Ling et al. used sandwich-layered silver nanowires that were 500 nm in width and 20 μm in length to construct SERS anti-counterfeit labels.^[7] The heterogenous multiplex label platform was created by using two-photon lithography via a direct laser-writing process followed by silver metallization and the addition of Raman probe molecules in an alternating fashion (Figure 8). Using SERS imaging at 1078 cm^{-1} , a Merlion symbol can be seen due to the existence of the functionalized 4-MBT. Then at 1200 cm^{-1} , the Merlion symbol could now be observed

with water gushing out of it. Here, a 4-MBT peak can be seen for the Merlion symbol but not the gushing water could be an extra layer of encryption in their anti-counterfeiting prospects.

3.4.2. Z-Dependent SERS Imaging

While most SERS imaging results in a 2D pattern, the Z-dependent SERS imaging represents a much rare scenario which can be an excellent opportunity as a hidden security feature. Currently, 3D SERS labels use the designed Raman "hot spots" at different laser confocal volumes, which allows for Z-dependent SERS images to be created. An example of 3D SERS imaging was accomplished using candlestick microstructures (Figure 9).^[29] Fabricated by two-photon laser lithography, the polymeric candlestick structures contained three different parts, a base pedestal, a middle dish, and a nanopillar on the top. Silver metal was then thermally evaporated onto the

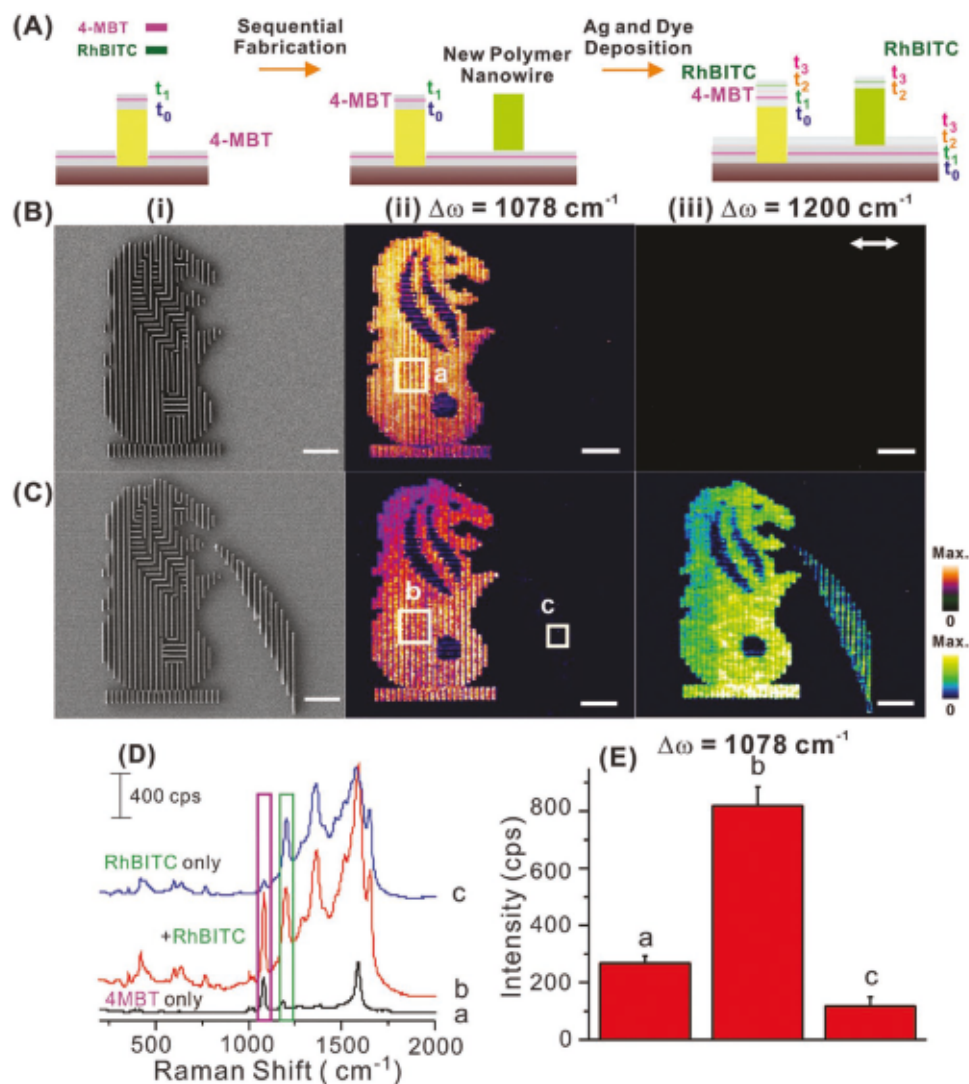


Figure 8. The a) fabrication and b,c) TEM images and SERS imaging of Merlion-shaped security labels based on heterogenous materials with 4-MBT and RhBITC probe molecules. d) SERS spectra and e) SERS intensity of the 1078 cm^{-1} peak from selected areas in (b) and (c). Scale bar: 10 μm . Reproduced with permission.^[7] Copyright 2015, Royal Society of Chemistry.

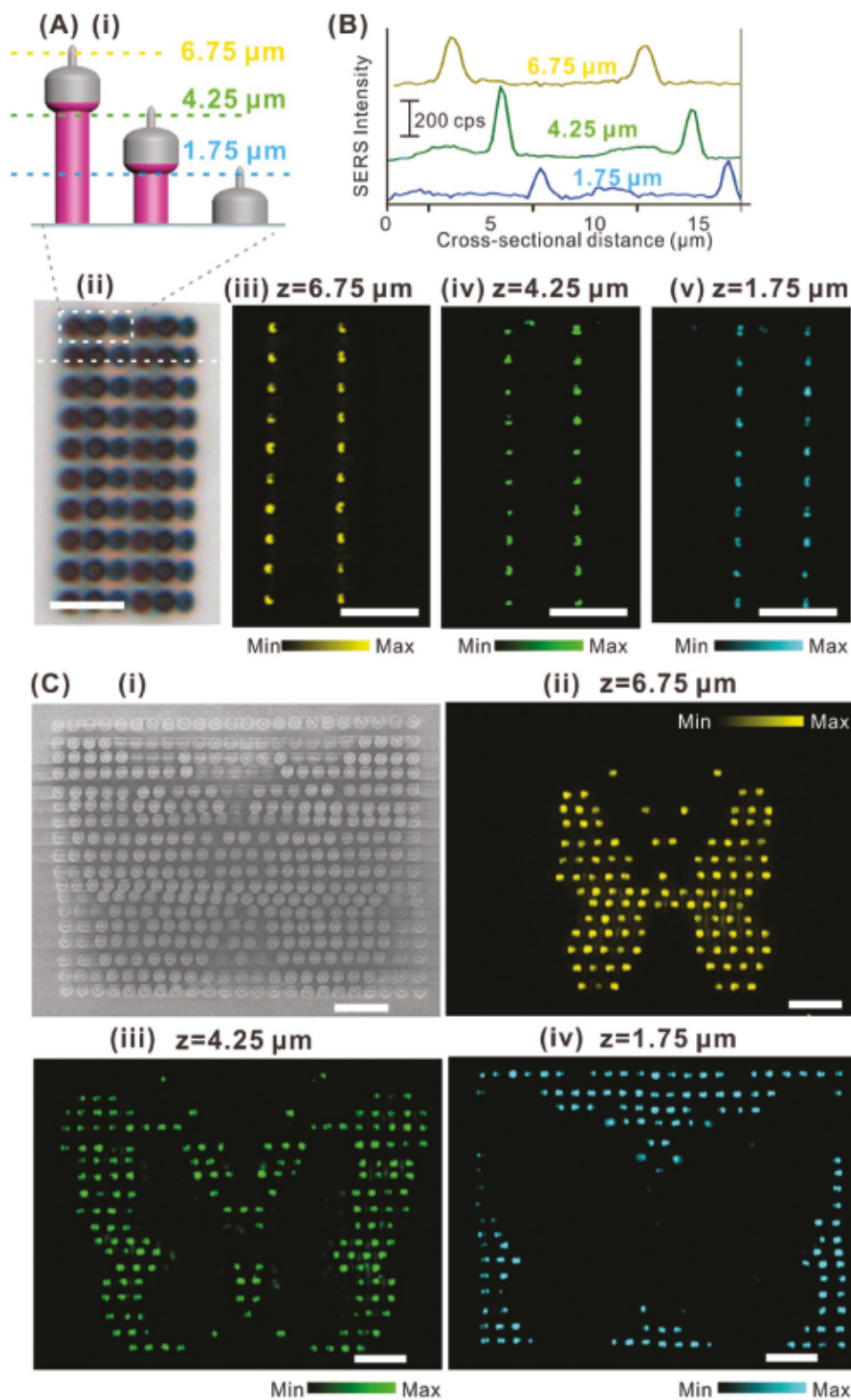


Figure 9. a) Scheme, optical image, and SERS image of Z-dependent SERS patterns using candlestick microstructure with three different heights. b) SERS intensity at the cross-section shown in (a). c) Z-dependent butterfly images were fabricated with varying heights of candlesticks. Scale bar: 10 μm . Reproduced with permission.^[29] Copyright 2017, American Chemical Society.

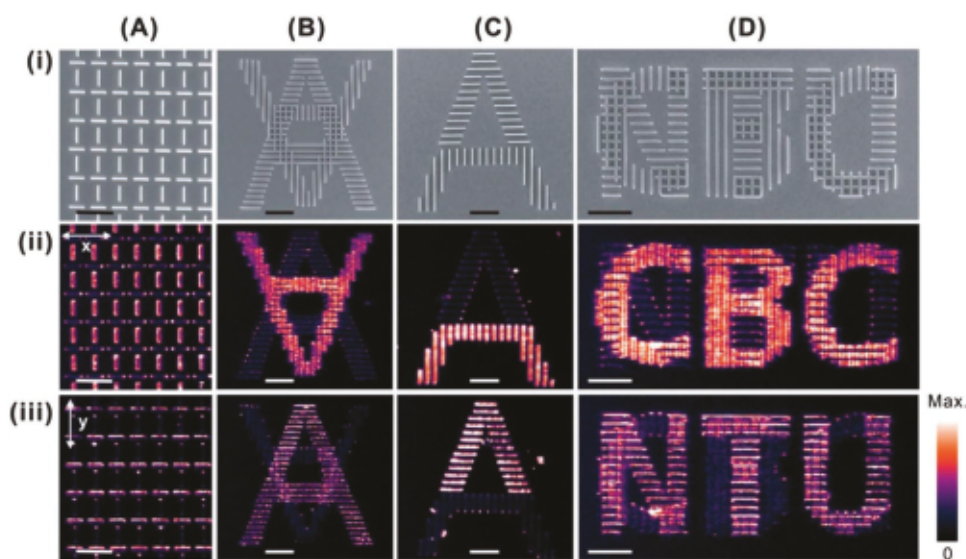


Figure 10. Images of various patterns composed of silver nanowires with *x*- and *y*-orientation: i) scanning electron microscope images; ii) SERS imaging with *x*-polarization; iii) SERS imaging with *y*-polarization. Reproduced with permission.^[22] Copyright 2014, Royal Society of Chemistry.

nanopillar and functionalized with 4-MBT. Using candlesticks with three different heights (7.5, 5, and 2.5 μm), the authors fabricated three-layered 3D SERS security labels. The three different candlesticks can be decrypted by SERS imaging at a given *z* value (6.75, 4.25, and 1.75 μm), and the results showed no signal crosstalk with the other pillars. Without knowing the heights needed for SERS imaging, decoding the 3D SERS labels becomes almost impossible.

3.4.3. Polarized SERS Imaging

Nanoscale materials also have many advantageous properties for anti-counterfeit applications, such as their polarization-dependent optical responses. For example, Cui and co-workers fabricated SERS labels with aligned silver nanowires, which results in SERS images that are dependent on the polarization of the excitation laser (Figure 10).^[22] The silver nanowires are sensitive to the polarization of the excitation laser. Strong electromagnetic field enhancement can be achieved when the incident light is perpendicular (*x*-axis) to the long axis of silver nanowires. When incident light is parallel (*y*-axis), the enhancement is very modest. Such polarization dependence allowed the creation of *x* and *y*-polarized 2D SERS images, where two messages can be encrypted using one set of SERS substrates, which are readily read out independently via tuning the incident polarized light in a particular orientation. This concept has been further expanded in follow-up studies where multiple Raman probe molecules have been used.^[7] Another study used aluminum nanostructures as a cheaper alternative to facilitate its practical application in anti-counterfeiting.^[30]

4. SERS Labels Combined with Other Techniques

New territories have started to be explored where researchers can utilize the SERS technique with other types of encoding

methods. The integration of various techniques can dramatically increase the sophistication of the SERS-based anti-counterfeit labels. In this section, SERS labels will be discussed in combination with fluorescent probes, barcodes, QR codes, and unclonable patterns, respectively.

4.1. SERS Labels with Fluorescent Reporters

Novel SERS techniques have been combined with other well-developed anti-counterfeiting strategies, such as fluorescent probes, to make even complicated security labels for higher-level anti-counterfeiting applications. For example, Wang and co-workers prepared dual-mode magnetic microspheres containing fluorescence reporters and SERS probes.^[79] As shown in Figure 11, the fluorescence spectra and the SERS spectra can be measured on these dual-mode microspheres. The authors then applied a binary coding method and converted the complicated fluorescence and SERS spectral information into simple binary codes according to an established spectral database. Without a doubt, the combination of fluorescence reporters with SERS reporters can significantly enlarge the encoding capacity. The authors treated the fluorescence information as a relatively low level of security that can be fast and effectively detected, while the SERS information was used at a higher security level that contained a fingerprint and characteristic information with a much larger encoding volume. Furthermore, the authors successfully demonstrated several outstanding properties of their dual-coded microspheres, including ultra-sensitive, simple, easily read out in situ, and suitable as covert tags for real anti-counterfeiting applications.

4.2. SERS Labels with Barcode

Since SERS images are invisible to standard optical microscopes, there is a great potential to use the SERS labels as

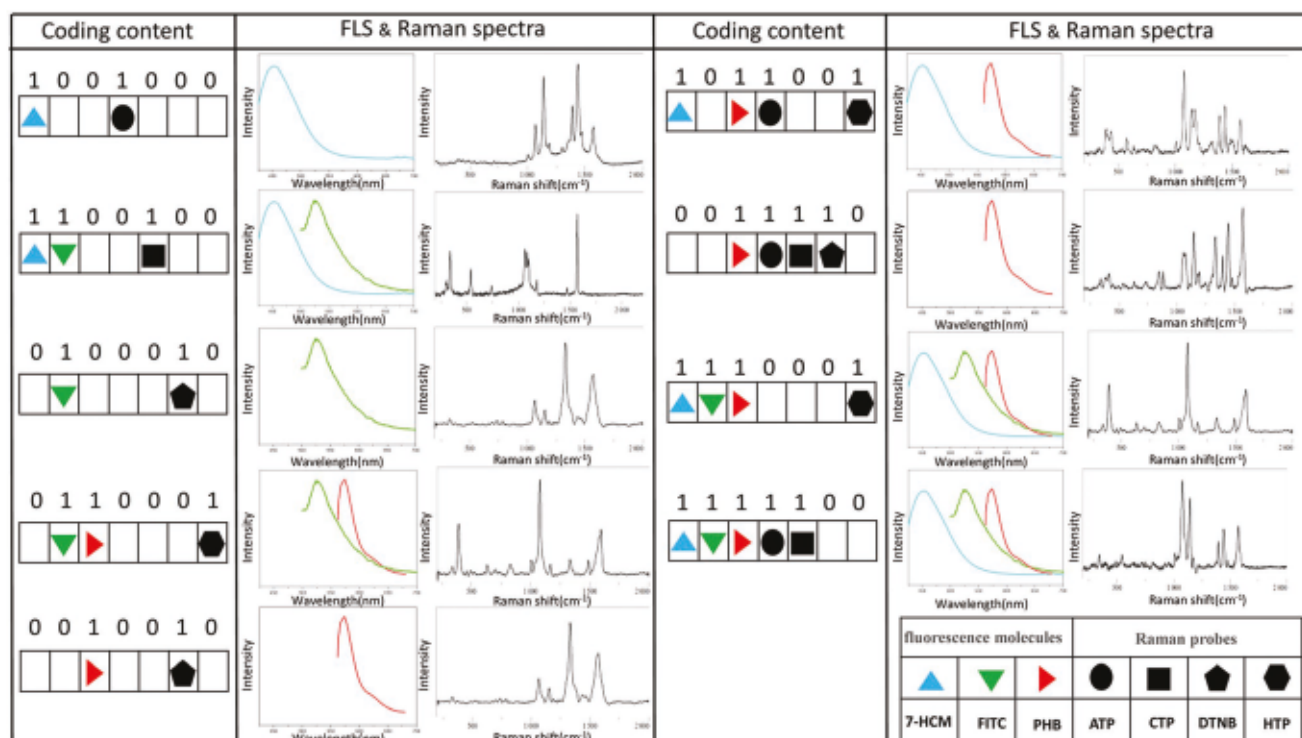


Figure 11. The binary coding of fluorescence and Raman spectra using selected probe molecules. Reproduced with permission.^[79] Copyright 2016, American Chemical Society.

barcodes in anti-counterfeiting.^[14] Liu and co-workers reported the preparation of multidimensional SERS barcodes using a simple lithography-free approach.^[25] They used silver nanocubes as SERS active substrates and fabricated the barcodes accordingly to the conventional Code-93 rule, which allows the barcodes to be recognized by a smartphone. The authors further increased the information capacity of these SERS barcodes by applying different types of Raman probe molecules and varying the concentrations of these molecules. As illustrated in Figure 12, the total number of codes can be as high as 5 011 875 when four types of Raman probes and three levels of concentrations are used in the barcode fabrication. In addition, the authors demonstrated that these flexible SERS barcodes could be easily applied to various surfaces, be laminated, and remained stable even when exposed to water immersion, mechanical deformation, or oxygen plasma treatment.

4.3. SERS Labels with QR Code

In addition to the SERS barcode technique, one can also use SERS-active substrates to make more complex patterns such as QR codes which will be quickly read out by specific QR-reader software in a smartphone. Compared to barcodes, QR codes can have much higher storage capacity and complexity. For example, Ying and co-workers reported a fabrication method for flexible patterned plasmonic metasurfaces using laser engraving machining.^[26] In their work, the first encryption layer is the conversion of an original text string “ZJU” into a cipher-text that was stored in the QR pattern. As the second encryption

layer, they stored the decipher key using SERS encoding in which an SERS spectral library was used. As demonstrated by the authors, the original information can only be revealed by decryption of both layers. Such multiple encryption layers can achieve a higher level of security in protecting important information, which could be a valuable tool in anti-counterfeiting.

To further increase the sophistication of SERS-based security labels for higher-level anti-counterfeiting applications, additional steganography was applied to the QR codes. Ling and co-workers fabricated anisotropic plasmonic aluminum nanostructures with polarization-dependent SERS response and successfully designed microsized security labels with a set of cipher-texts overlaid on microsized QR codes.^[30] As shown in Figure 13, the encoded information cannot be revealed using simple physical characterization techniques such as scanning electron microscopy. With a procedure of SERS imaging, a 2D barcode can be obtained when acquiring the *x*-polarized SERS images based on the 1330 cm^{-1} peak of the probe molecule, naphthalene. Such QR codes can directly guide users to the coded website. On the other hand, a *y*-polarized SERS image must be used to discern the secret message. These multiple security features could be very critical for protection against forgery.

4.4. SERS Labels with Unclonable Pattern

An even more sophisticated approach in making anti-counterfeit labels is to combine SERS with unclonable patterns.^[98,99] Recently, there have been some reports on fabricating anti-counterfeit labels based on physically unclonable functions

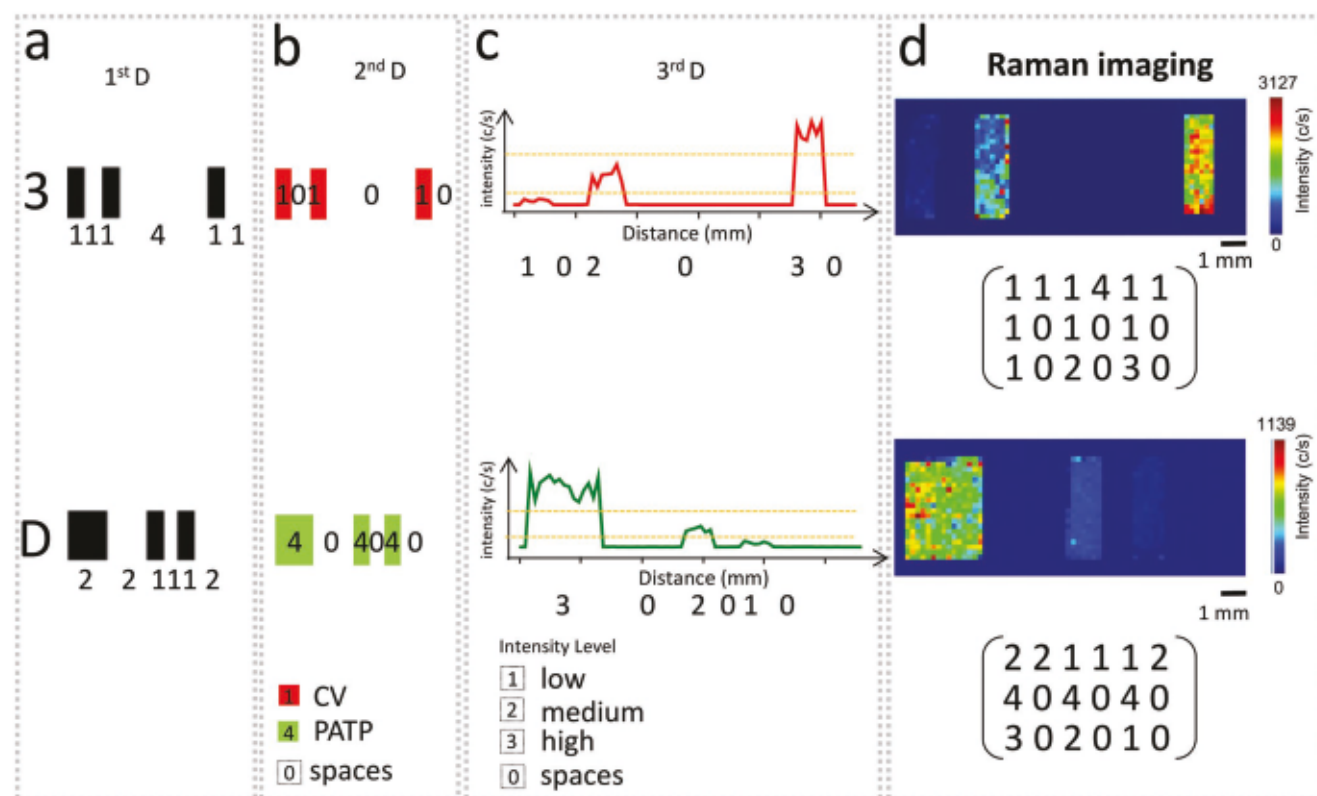


Figure 12. 3D SERS barcode illustration. The three dimensions are shown in (a)–(c), while (d) shows the Raman imaging of the barcode. Reproduced with permission.^[25] Copyright 2016, Wiley-VCH.

(PUFs). Due to the uniqueness of the PUFs, these counterfeit labels can have an enormous security capacity, and they are virtually impossible to replicate. The involvement of the SERS technique adds a layer of security measures that can result in much better anti-counterfeiting materials.

Plasmonic nanogel coatings, e.g., were prepared by Singamaneni and co-workers to use as unclonable optical tags, in which dual topo-chemical encoding was achieved by randomly adsorbing two types of Raman reporters in the folded regions of plasmonic films. In their work, poly(2-vinylpyridine) (P2VP) thin films were prepared with spinning coating, and thiol-terminated gold nanorods were then assembled on these films.^[28] Randomized networks of interacting folds were then prepared using a swelling-mediated method. The fold patterns were formed in a nondeterministic manner, which is very suitable for anti-counterfeiting applications for resource-limited settings. The SERS data of Raman reporters in the regions of interest provided additional dimensions for the security labels. It is found that the folding-induced electromagnetic hotspots can have stronger SERS signals than their surroundings, thus SERS mapping can be obtained from those SERS labels. As shown in Figure 14, SERS maps of p-aminothiophenol and 2-nitrophenol can be obtained, respectively. Furthermore, an SERS map of intensity ratio can be obtained, which is associated with the stochastic distribution of Raman reporters in the folding-induced electromagnetic hotspots. Such SERS ratio maps can be utilized as a higher-level security feature, which are invisible to usual optical microscopy, and are nearly

impossible to replicate. For example, the authors clearly showed that obtaining such SERS ratio maps is impossible if the swell-mediated fabrication process was not used.

Recently, Ye and co-workers reported the use of core-shell SERS nanoparticles to fabricate SERS-based PUF anti-counterfeit labels.^[31] In their work, Raman reporters with thiol groups were embedded in core-shell gold nanoparticles to form GERTs, which can be excited by a 785 nm near-infrared laser. These GERTs have strong SERS signals, long shelf-life time, and are very photostable. A random distribution of one type of GERTs can form stochastic nanoscale patterns, which can easily give a coding capability of 3.8×10^{752} when a resolution of 50×50 pixel was used. Using multi-types of GERTs can further increase the dimension of encoding. An example of using these GERT PUF labels was presented in their work with sufficient coding capacity and an acceptable error margin. In addition, the authors also developed a high-speed readout system for their designed GERT PUF labels.

5. Conclusion and Outlook

Anti-counterfeiting technology is important for the protection of our well-being. Anti-counterfeit labels, with secret information stored within them, are being used to reduce the damage caused by the widespread counterfeit problem. Due to novelty and close relation to molecular identity, Raman scattering is a great candidate to be used for anti-counterfeit, especially in

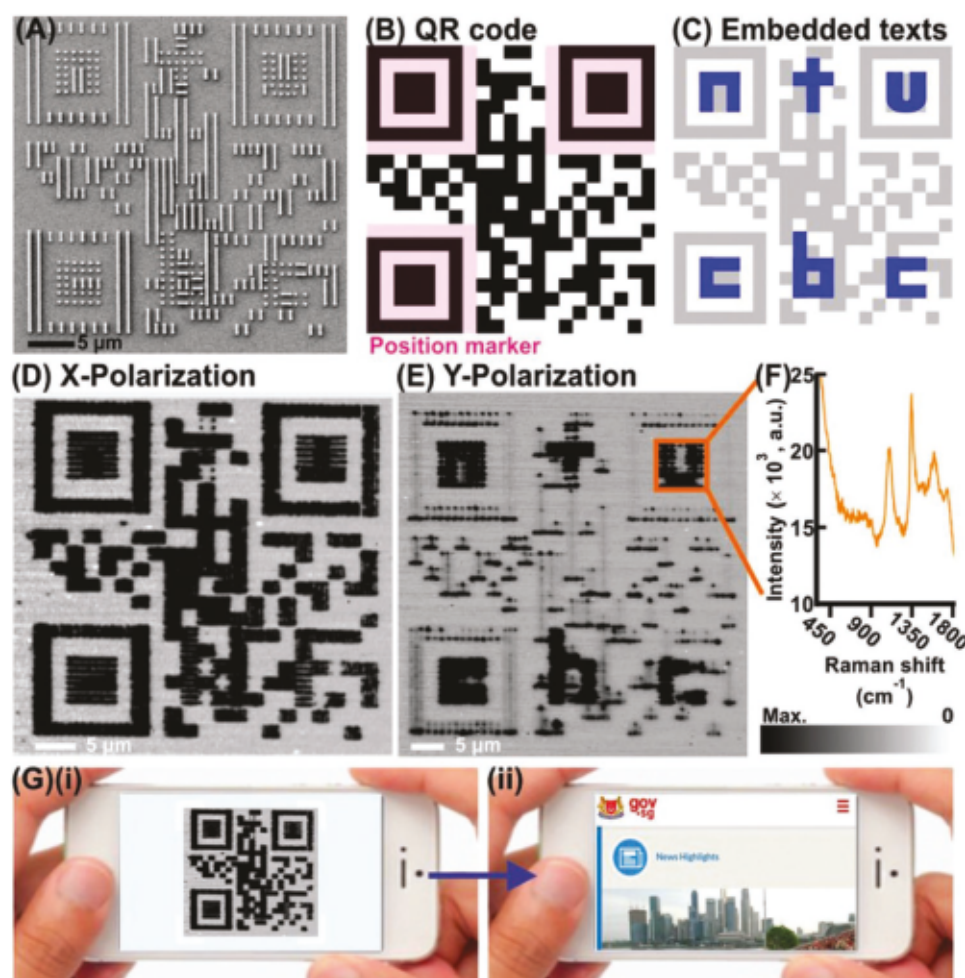


Figure 13. a) The scanning electron microscopy image of a fabricated b) QR code of the Singapore government website with c) embedded ciphertext. d,e) Raman imaging with different polarization lights to show the QR code as well as the embedded ciphertexts. The image used NAP probe molecules with spectrum shown in (f). g) Demonstration of reading a QR code using a smartphone. Reproduced with permission.^[30] Copyright 2018, Royal Society of Chemistry.

making anti-counterfeit labels. Moreover, SERS as a special technique of Raman scattering provides enormous Raman signals, which is the key for application developments of SERS anti-counterfeit labels.

In this review, we discussed the usage of Raman in the field of anti-counterfeiting and focused on the development of SERS-based anti-counterfeit labels. The fabrication of SERS labels requires suitable plasmonic materials to be the SERS-active substrates and Raman probe molecules to provide secret spectroscopic information. Plasmonic nanomaterials have proved to be good candidates in making the anti-counterfeit labels, while a lot of thiolated molecules and dye molecules were used as Raman reporters. We further discussed the two main approaches to store secret information into SERS anti-counterfeit labels. The first approach focuses on the identity of the SERS spectrum, which is based on the difference in the vibrational modes of probe molecules and the selection of substrates. The second approach is to fabricate various SERS patterns by arranging the Raman probe molecules or the design of the physical shapes of substrates. These two approaches lead to

the SERS anti-counterfeit labels with high information capacity. Furthermore, SERS labels are also often combined with other anti-counterfeiting methods to achieve multilayer security. Such methods can be either physical anti-counterfeiting patterns like QR code and barcode, or spectroscopic type information like fluorescence. Meanwhile, a new advanced technique named “unclonable” labels brings an even higher security level to SERS labels. Overall, we concluded the foundations and the advancements in the design of SERS anti-counterfeit labels and believed that these methods could help the further advancement of anti-counterfeit labels.

SERS anti-counterfeit labels are a type of anti-counterfeiting method that could reach high security and high flexibility. On the one hand, this label is suitable for commercial applications to integrate into consumer products to monitor the counterfeit activities on the supply chains. On the other hand, in cryptography, the unique spectroscopic coding is different from conventional mathematical coding, which could be a novel approach to generate asymmetric keys for business security or homeland security applications. However, there are several

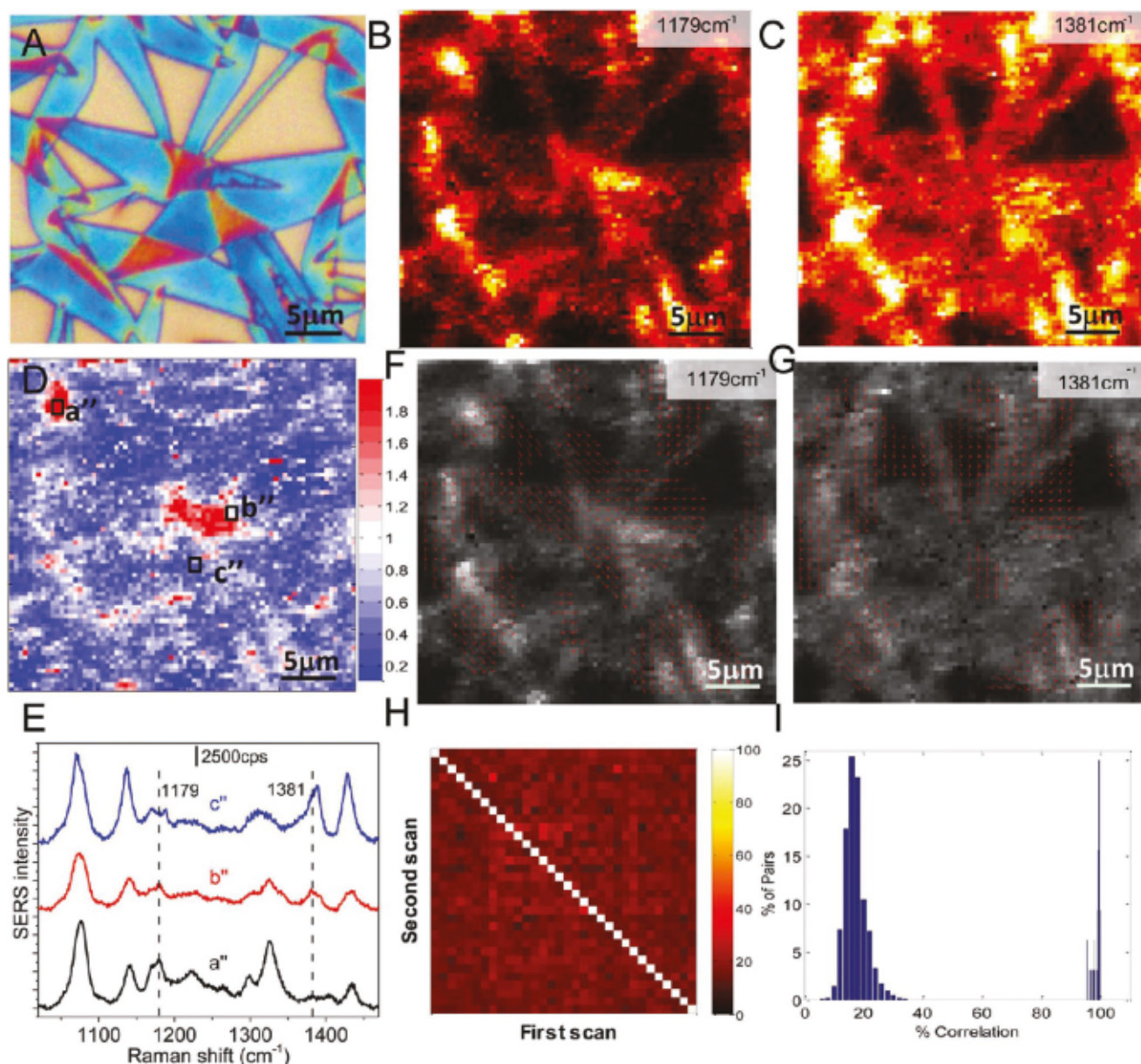


Figure 14. a) Optical and b, c) SERS intensity maps of plasmonic nanogels with random patterns. The intensity ratio map is shown in (d) and the typical SERS spectra are shown in (e). f, g) The vector distribution of the SERS intensity map, which was used to calculate the correlation of the samples, and the results were presented through h) heat map and i) histogram. Reproduced with permission.^[28] Copyright 2016, American Chemical Society.

bottlenecks for the SERS anti-counterfeit labels to be widely used. One of them is to develop a reproducible synthetic procedure for SERS-active nanostructures with high sensitivity and long-term stability in large-scale productions. The practical applications of SERS anti-counterfeit labels will not be possible without the successful production of reliable SERS-active nanostructures. Also, devices with fast Raman mapping and vast spectra analysis abilities should be further improved for the recognition of SERS labels. Currently, handheld Raman readers with performance almost comparable to desktop Raman spectrometers are commercially available. Further advances in the miniaturized photodetectors could provide higher sensitivity for SERS label recognition. In addition, those handheld devices

are rather costly, which could be an issue to some of the stakeholders, including manufacturers, distributors, retailers, and, especially to consumers. In the future, Raman reader might be an add-on component to a smart phone, which can dramatically broaden its user base. Furthermore, the development of wearable smart devices will increase the chance to integrate Raman readers into smart glasses and wrist bands. Meanwhile, advanced techniques such as cloud storage, big-data science, artificial intelligence,^[100] and the Internet of Things, might all play some essential roles in the further development of SERS-based anti-counterfeit labels. In this case, these SERS labels will have even broader applications in various scenarios of anti-counterfeiting.

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Conflict of Interest

The authors declare no conflict of interest.

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anti-counterfeit labels, security labels, surface-enhanced Raman scattering

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