Plasma based Structured Illumination Microscopy

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1 Abstract

We propose a high-resolution nanoscopy technique using two-dimensional plasma waves generated in a semiconductor heterostructure. The working principle is similar to structured illumination microscopy augmented by the high spatial frequency ans tunability of plasmons yielding resolution up to two orders of magnitude beyond the diffraction limit. The nature of the technique is linear, meaning a weak illumination signal is required, minimizing the chances of radiation damage of sample. We present a linear high-resolution imaging scheme based on the plasma waves originating in the channel of field-effect transistors. The extremely small plasmonic wavelength along with a tunable illumination pattern in the far infrared region can resolve nano-scale objects over a broad range of frequencies.

In conventional wide-field fluorescent microscopy, a sample to be imaged is uniformly illuminated by light and the subsequent fluorescence is observed in the far-field through the objective of the microscope. The uniform nature of the illumination fundamentally restricts the resolution of the system to half the wavelength of light due to Abbe diffraction limit. With ever growing need to image tiny objects particularly in life sciences, modern microscopy techniques such as confocal and linear structured illumination microscopy use spatially non-uniform sources to illuminate the sample, resulting in resolution extending beyond the diffraction limit by a factor of 2 [1, 2]. In confocal microscopy, a small portion

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of sample is illuminated by a focused beam generated through a pinhole. The beam is laterally shifted to completely scan the sample, creating a sequence of images. Each image passes through another pinhole on the detector side. A high resolution image of the sample is generated by processing the image sequence, however confocal microscopy is a slow imaging technique. Moreover, part of light is discarded by the pinhole which may leave the signal strength from weakly fluorescent samples undetectably low. Structured Illumination microscopy (SIM) is a wide-field technique in which a fine illumination pattern such as a sinusoidal standing wave is used to generate *Moiré fringes* in the observed image. The high frequency content is mathematically reconstructed from a series of images acquired by shifting the pattern, yielding a high resolution image.

2 Principle of Structured Illumination Microscopy

Consider $I(\mathbf{r})$ as the sinusoidal illumination intensity:

$$I(\mathbf{r}) = 1 + \cos\big(\mathbf{k}_\rho \cdot \mathbf{r} + \phi\big) \tag{1}$$

where $\mathbf{k}_\rho = k_x\hat{\mathbf{x}} + k_y\hat{\mathbf{y}}$ is the spatial frequency wavevector, $\mathbf{r} = x\hat{\mathbf{x}} + y\hat{\mathbf{y}}$ is the two-dimensional positional vector and ϕ is the pattern phase. The image of a sample $F(\mathbf{r})$ observed through a microscope can be expressed as:

$$M(\mathbf{r}) = \big[F(\mathbf{r}) \cdot I(\mathbf{r})\big] \otimes H(\mathbf{r}) \tag{2}$$

where $H(\mathbf{r})$ is the point spread function (PSF) of the microscope, and $\cdot, \otimes$ denote multiplication and convolution operations in the spatial domain respectively. A frequency domain representation of the image by taking the Fourier transform is expressed as:

$$\begin{aligned} \tilde{M}(\mathbf{k}) &= \Big[\tilde{F}(\mathbf{k}) \otimes \tilde{I}(\mathbf{k})\Big] \cdot \tilde{H}(\mathbf{k}) \\ &= \frac{1}{2}\Big[2\tilde{F}(\mathbf{k}) + \tilde{F}(\mathbf{k}-\mathbf{k}_\rho)\mathrm{e}^{-j\phi} + \tilde{F}(\mathbf{k}+\mathbf{k}_\rho)\mathrm{e}^{j\phi}\Big] \cdot \tilde{H}(\mathbf{k}) \end{aligned} \tag{3}$$

where $\sim$ over the letters indicates a frequency domain term and $\tilde{H}(k)$ is the optical transfer function (OTF) of the microscope. As evident in (3), a sinusoidal illumination pattern has three frequency components which generates an image which is linear combination of the sample along with two shifted versions as shown in Fig. 1(b). To reconstruct the sample, three different images need to be captured with different phase term ϕ. The

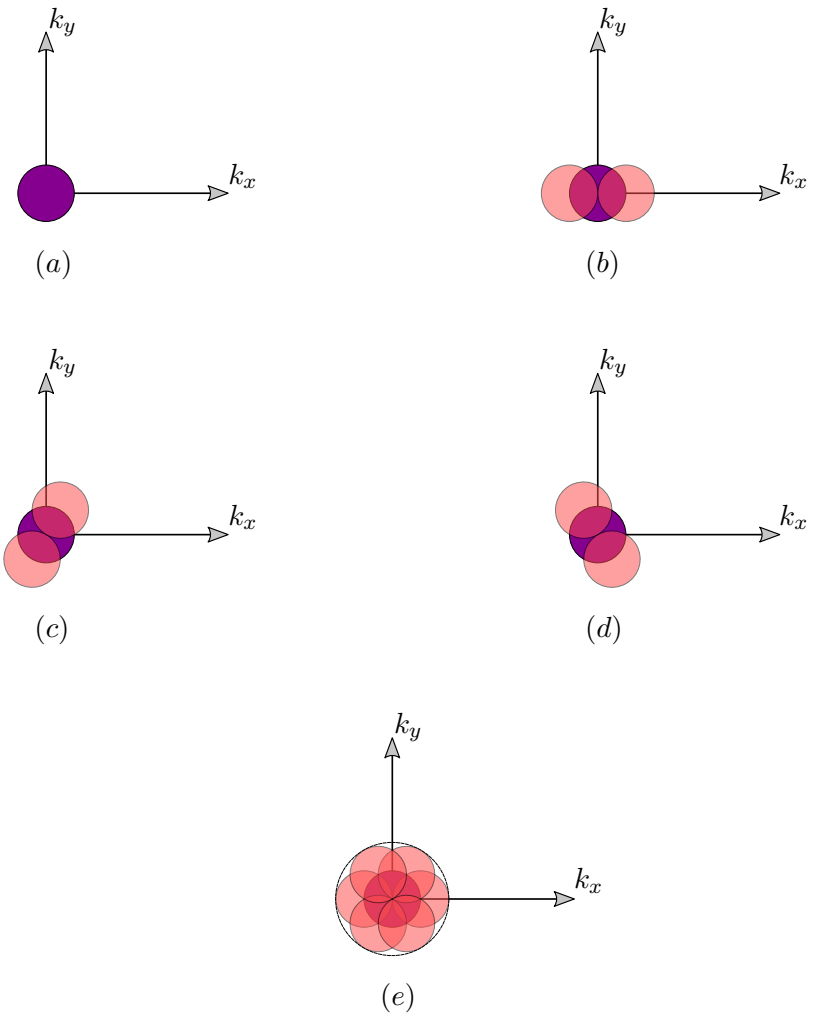

Figure 1: Resolution enhancement through SIM: (a) Diffraction limited observable region in frequency domain. Moiré effect using a sinusoidal illumination pattern bringing high frequency content under the observable region. The sample is rotated: (b) 0°, (c) 60°, (d) 120°. (e) Doubling of lateral resolution with effective coverage area twice the size of (a)

process can be expressed as a system of linear equations,

$$\tilde{H}(\mathbf{k}) \cdot \begin{bmatrix} \tilde{F}(\mathbf{k}) \\ \tilde{F}(\mathbf{k}-\mathbf{k}_\rho) \\ \tilde{F}(\mathbf{k}+\mathbf{k}_\rho) \end{bmatrix} = \begin{bmatrix} 2 & \mathrm{e}^{-j\phi_1} & \mathrm{e}^{j\phi_1} \\ 2 & \mathrm{e}^{-j\phi_2} & \mathrm{e}^{j\phi_2} \\ 2 & \mathrm{e}^{-j\phi_3} & \mathrm{e}^{j\phi_3} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{M}_1(\mathbf{k}) \\ \tilde{M}_2(\mathbf{k}) \\ \tilde{M}_3(\mathbf{k}) \end{bmatrix} \tag{4}$$

The phase shifts in (4) are known beforehand. Frequency content of the sample up to k_ρ can, therefore be observed due the Moiré effect which transports the high frequency information in to the observation region. To achieve two-dimensional enhancement in

resolution, the sample has to be rotated about the optical axis of the microscope or the angular distribution of the illumination needs to be varied.

$$\omega_p^2 = \frac{N_s e^2 k}{m^* \varepsilon} \left(1 + \frac{\varepsilon - 1}{\varepsilon + 1} \mathrm{e}^{-2kkd}\right) \tag{5}$$

where N_s is the surface charge density, e is the electron charge, m_* is the effective electron mass, ε is the average dielectric constant of surrounding media, and d is the separation between the gate terminal and sheet of charge as shown in Fig. 1. The plasma resonance can be tuned by up to an order of magnitude by varying the 2D electron density with the gate bias.

$$N_s = N_0 \times (1 - \frac{V}{V_T}) \tag{6}$$

3 Theory

In gaseous plasma, current-driven instabilities lead to generation of plasma waves requiring very high carrier drift velocities. An analogous effect can be observed in solid-state devices, particularly in a two-dimensional electron gas that is formed at the interface of eptixially grown semiconductors with slightly different band gaps. Remarkably high carrier density and high mobility of the 2DEG enable large drift velocities that lead to plasma wave generation. The proposed imaging scheme is illustrated in Fig. 2 where the sample is placed above a back gated high electron mobility transistor (HEMT) in which 2DEG serves as the device channel. With highly conducting boundaries in the form of source and drain terminals, the plasma waves are reflected, creating a standing wave pattern in the channel cavity. The plasma frequency for a channel of length L is expressed as [**?**]:

$$\omega_p = \sqrt{\frac{N_s e^2 d}{m_* \varepsilon}} \frac{\pi}{L} \tag{7}$$

where N_s is the surface charge density, e is the electron charge, m_* is the effective electron mass, ε is the average dielectric constant of surrounding media, and d is the separation between the gate terminal and sheet of charge as shown in Fig. 1. The plasma frequency can be tuned by varying the charge density through the gate voltage V_g:

$$N_s = \frac{\varepsilon}{ed}(V_g - V_t) \tag{8}$$

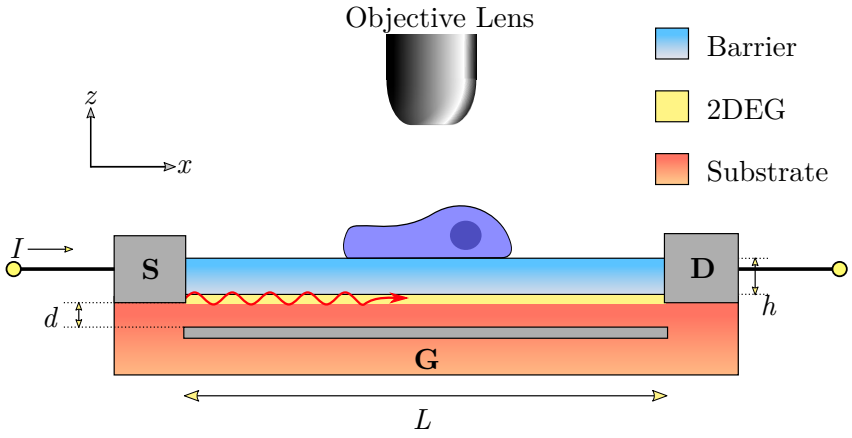

Figure 2: Sample placed on top of HEMT with back gate and excited by 2D plasmons generated by a direct current

where V_t is the gate threshold voltage. To derive the dispersion relation, the 2DEG is described by a surface conductivity function:

$$\sigma_s(\omega) = \frac{N_s e^2 \tau}{m^*} \frac{1}{1 - j\omega\tau} \tag{9}$$

where τ is the scattering time of electrons in the channel.

References

[1] M. Minsky, "Memoir on inventing the confocal scanning microscope," *Scanning*, vol. 10, no. 4, pp. 128–138, 1988.

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[3] V. V. Popov, A. N. Koudymov, M. Shur, and O. V. Polischuk, "Tuning of ungated plasmons by a gate in the field-effect transistor with two-dimensional electron channel," *Journal of Applied Physics*, vol. 104, no. 2, p. 024508, Jul. 2008.