Detection of Subsurface, Nanometer-Scale Crystallographic Defects by Nonlinear Light Scattering and Localization

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Heteroepitaxial crystalline films underlie many electronic and optical technologies but are prone to forming defects at their heterointerfaces. Atomic-scale defects such as threading dislocations that propagate into a film impede the flow of charge carriers and light degrading electrical/optical performance of devices. Diagnosis of subsurface defects traditionally requires time-consuming invasive techniques such as cross-sectional transmission electron microscopy. Using III–V films grown on Si, noninvasive, bench-top diagnosis of subsurface defects have been demonstrated by optical second-harmonic scanning probe microscope. A high-contrast pattern is observed of subwavelength “hot spots” caused by scattering and localization of fundamental light by defect scattering sites. Size of these observed hotspots are strongly correlated to the density of dislocation defects. The results not only demonstrate a global and versatile method for diagnosing subsurface scattering sites but uniquely elucidate optical properties of disordered media. An extension to third harmonics would enable irregularities detection in non-$\chi^{(2)}$ materials making the technique universally applicable.

1. Introduction

III–V epitaxial films are excellent candidates for high-speed electronic and opto-electronic devices, semiconductor spintronics, nanometer scale logic transistors, nanowire channels, and light emitters on the industry-standard Si (001) platform.[1–3] Due to their superior carrier mobility, III–V carrier transport channels can improve the performance of silicon-based logic transistors by enabling reduced operating voltage,[2] thus addressing the obstacle of power dissipation.[4] However, III–V films on Si are prone to formation of defects, including threading dislocations (TDs), because of lattice mismatch at the heterointerface. Given the detrimental effects of such atomic defects on the electronic and photonic response of the III–V films, it is of crucial importance to develop techniques for detecting defects. This work reports sub-micrometer optical signatures of subsurface dislocation defects by collecting and selectively filtering femtosecond-laser-generated second-harmonic generation (SHG) radiation from the sample through a 50 nm aperture fused silica probe (see description of aperture in the Experimental Section). When the probe is scanned, samples laden with subsurface defects uniquely exhibit prominent “hotspots” (i.e., locally intense SHG signal) due to near-surface intensity spikes created by scatter and localization of the fundamental field from the buried defects. The density, size, and pattern of these hotspots depend on the defect density and wavelength of the incident fundamental light but are not affected by and uncorrelated with the topology of the sample surface. Control
samples without defects (e.g., homoepitaxial GaAs–GaAs films) lack such defect-related signatures. We observe no comparable signature using conventional linear optical probe microscopy, which is instead dominated by surface reflection and topology, nor using conventional far-field reflected SHG without probe collection, which is dominated by antiphase-domains at the film surface. Thus, second-harmonic probe microscopy (SHPM) relies on both second-order nonlinearity and subwavelength collection and can uniquely detect buried dislocation defects in semiconductors films noninvasively without sample preparation. 

Microscopy community were capable of detection of subsurface structures noninvasively,[5,6] in contrast, most traditional techniques for diagnosing subsurface dislocation defects require special, often invasive, sample preparation, e.g., electron microscopy and crystallographic etches.[7,8] Some such as Bragg coherent diffraction[9] require access to a large-scale light-source facility.

2. Results and Discussion

Figure 1a shows our approach for SHPM schematically. A near-infrared laser pulse penetrated the film and scattered from subsurface defects. Semiconductor III–V films like GaAs on Si (001), because of 4.2% lattice mismatch at the interface, have a high density of TD defects which penetrate through the ≈500 nm top-layer GaAs and reach the surface of the sample. They appear with good contrast[10] in cross-sectional scanning transmission electron microscopy (STEM) images, e.g., Figure 1b (bottom). Light localization due to interference among multiply elastically backscattered waves[11–14] creates a network of intensity spikes and nodes of subwavelength lateral dimension within the film. Interest in manipulating photons on a subwavelength scale analogously to electrons has resulted in influential discoveries such as Anderson light localization,[11,15] nearfield optics,[16] and optical transmission through subwavelength hole.[17] Light localization has been observed in non-conductive disordered media,[15,18–20] conductive disordered media,[21] nonlinear disordered media,[22,23] photonic crystals,[24] and photonic Moiré lattices.[25] Even localization in cold atoms in 3D and Bose–Einstein condensation[26,27] are analogous to light localization.

Since SHG intensity depends quadratically on fundamental wave intensity $I_\omega$

$$I_{sh} \sim \left[\chi^{(2)}\right]^2 I_\omega^2 \tag{1}$$

(where $\chi^{(2)}$ is the local second-order nonlinear optical susceptibility) which we explicitly confirmed for all results reported here (Figure S1, Supporting Information), the SHG process enhances the contrast between local spikes and nodes at fundamental intensity. SHG filtering eliminates the strong laser reflection from the surface that washes out the weaker backscattered and localized fundamental light. With a fiber-based probe scanning ~20–30 nm above the sample surface we collected back-propagating SHG light. These scans generated images showing local SHG intensity variations with transverse resolution determined by aperture size and scan step size. This microscopy system includes a fiber probe, filters, and photo multiplier tube suppressing fundamental light by a factor of $10^{22}$ compared to SHG.

Figure 1b (top) shows a SHG hotspot pattern from a 500 nm GaAs film grown on a Si substrate off-cut 4° from (001). This
off-cut creates terraces separated by double-atomic-height steps that eliminated anti-phase domains (APDs). However, TD density, determined from planar and cross STEM images, is $10^9 \text{cm}^{-2}$. A similar scan of a reference GaAs–GaAs sample free of any subsurface defects, on the other hand, yields a uniform SHG signal free of high-contrast texture (Figure 1c top). The maximum intensity of hotspots in the GaAs–Si-off axis scan exceeds SH intensity from the reference film approximately fourfold. This increase in intensity of reflection from disordered media has been previously attributed to Anderson localization of light.[28]

Several cross-checks confirmed our interpretation of the SHPM signal. First, the SHG signal depended quadratically on fundamental excitation intensity (Figure S1, Supporting Information). Second, we confirmed that the spectrum of the collected signal contained only frequency-doubled fundamental light (Figure S2a, Supporting Information). This ruled out the possibility that fundamental light could leak through the fiber probe shaft and become the source for different frequency light. Third, we scanned a prefabricated subsurface sub-micrometer-scale structure, alternating strips of InP and SiO$_2$, and observed matching SHPM patterns (Figure S2b, Supporting Information). Finally, we checked the reliability of SHG features by scanning neighboring regions independently and showing that optical hotspots matched on the two sides (Figure S2c, Supporting Information).

SHPM scans over nanometer-sharp edges of the $\approx 70 \text{nm}$ wide InP/SiO$_2$ structure yielded a point spread function (PSF) of the scanning probe microscope system (Figure S3, Supporting Information). The derivative of this edge signal yielded a peak of $\text{FWHM} \approx 27 \text{nm}$, which defines the resolution of the system. This PSF has been deconvoluted from scanned images to reveal their native profiles. The observation of SHG hot spot features as small as $\approx 50 \text{nm}$ FWHM, well below the diffraction limit, in high-defect-density samples (Figure S4d, Supporting Information) corroborates this figure. All the observed hotspot profile patterns have exponentially decaying tails/wings, as expected for Anderson localization.[22,29] (Figure S5a–f, Supporting Information). The observed optical hotspot intensity distribution also shows a log-normal distribution which is the signature of localization.[29–31] (Figure S5g,h, Supporting Information). Thouless Conductance “$g$” was estimated by fitting the probability distribution of normalized intensity as well (Figure S6, Supporting Information). Numerical calculation (Figure S7, Supporting Information) shows the resolving power of the 50 nm size probe as $\approx 30–35 \text{ nm}$ by scanning over point-like electric field sources and replicated sharp optical edge.

Sub-micrometer bright and dark spots such as those shown in Figure 1b, could also arise from local defect-related variations in the film’s $\chi$($\omega$), rather than from variations in $I_\omega$. To test this possibility, we tuned the incident wavelength. A fixed spatial pattern of $\chi$($\omega$) variations should retain a fixed shape as the excitation wavelength changes, even though the intensity of individual features may vary. On the other hand, the locations of hotspots in the backscattered pattern depend on interference, and thus on wavelength. Figure 2 shows two examples of how the observed SHPM pattern evolves as the excitation (collection) wavelength tunes from 840 (420 nm) (a,d) to 780 (390 nm) (b,e). Figure 2a,b is raster scans of the same $2 \times 2 \mu \text{m}$ area of a GaAs (500 nm)-Si (001)-on axis sample, Figure 2d,e of a GaAs (500 nm)-Si (001)-4° vicinal sample. In both cases, the location of hotspots is completely different at these two wavelengths. At intermediate wavelengths (not shown here), we observe that the patterns evolve continuously. In either case, however, we do not observe any correlation between the hotspot patterns and surface topographies, shown in Figure 2c,f, which correspond to rms roughness 2 and 16.5 nm, respectively, for the on- and off-axis samples.

By replacing the SHG bandpass filters on the detector with filters at the fundamental wavelength, we directly compare fundamental light scans with SHG scans. Figure 2g–i shows, respectively, a fundamental light (780 nm) scan, surface topography (derived from the probe feedback signal), and SHG scan of the same $2 \times 2 \mu \text{m}$ area of an oriented, 500 nm GaAs film grown on Si(001). The dominant features of the fundamental light scan (Figure 2g) closely match the main surface topographical features (Figure 2h). These linear features are also independent of wavelength: we observe them whether we illuminate the sample with fs-pulsed or continuous wave near IR light, incoherent white light, or frequency-doubled (390 nm) pulses (not shown). In contrast, the dominant features of the SHG scan (Figure 2i) obtained simply by switching filters and collecting only 390 nm light, are uncorrelated with either surface topography (Figure 2h), or with secondary features visible in the fundamental light scan (Figure 2g). Like the SHG scans of GaAs films (Figure 2a,d), the scan in Figure 2i depended strongly on wavelength. We observe similar trends on a wide variety of samples. Evidently, strong fundamental reflection from surface features masks the weak hotspots from subsurface defects, whereas SHPM better discriminates the latter.

To test the hypothesis that SHG hotspots originate from subsurface structures, we prepared a series of GaAs/Si(001) or InP/Si(001) samples with groove-like sub-micrometer-scale aspect-ratio trapping (ART) structures at the buried interface, similar to those used to obtain the PSF. These structures consist of parallel 170 nm high SiO$_2$ pillars fabricated on the offset Si (001) substrate along the [110] direction, separated by $\approx 70 \text{ nm}$ trenches, which GaAs or InP was deposited. Figure 2l shows a typical SHPM scan of such a sample. The grooved topology of the buried interface, though not precisely mapped, is clear evident in the SHG pattern, in contrast to those like Figure 2i. Fundamental wavelength scans (Figure 2j), on the other hand, are dominated by surface topography (Figure 2k). This demonstrates that subsurface structure is responsible for the broad features of the SHPM pattern. Inset SEM graph in Figure 2k shows the strip signature of these ART structures.

To better understand the structure of experimental SHPM patterns, we emulated near-field light scattering in III–V thin films using finite element calculations. These simulation data show GaAs–Si structures without dislocation scattering site (Figure 3a) low density of dislocation scattering sites (Figure 3b) and full of subsurface scattering sites (Figure 3c) that scatter light similarly to experimental results shown in Figures 1 and 2. Dislocation defects behave as acceptor traps for electrons and thus act as Coulomb scattering centers.[32] To emulate their scattering behavior, we assign them locally metallic properties.
Figure 2. Evolution of SHG optical domains at different excitation/collection wavelength and Comparison of fundamental and nonlinear (SHG) optical scan. a,b) SHPM plot of GaAs-Si-on axis at 420 nm (laser excitation at 840 nm) (a) and at 390 nm (laser excitation at 780 nm) (b) collected by SHPM probe. d,e) SHPM plot of GaAs-Si-off axis at 420 nm (laser excitation at 840 nm) (d) and at 390 nm (laser excitation at 780 nm) (e). Evolution of optical domains is observed for both samples as a function of wavelength. All the steps of evolution are not shown here. These evolutions shows that the variation of intensity is not due to variation of local $\chi^{(2)}$ and are strong signature of variation of fundamental intensity. This evolution also show how different wavelength takes different scattering paths. c,f) Topography collected by scanning probe microscope during the optical scan are shown in gray color. There is no correlation between optical map and topography of the sample. GaAs-Si-on axis (C) has $R_{\text{rms}} \approx 2$ nm roughness and GaAs-Si-off axis (f) has $R_{\text{rms}} \approx 16.5$ nm roughness. g–i) Fundamental scan of GaAs-Si-on axis (g) shows strong correlation to the topography (h) which was collected at the same time by the feedback loop system that controls the sample-probe distance. Profiles cuts in (g) and (h) show how topography is dictating in linear light study. Profile cut for topography is in nanometer unit and for linear scan is normalized counts per second. Excitation and collection were at 780 nm for linear study. Nonlinear scan (i) of the same area show signature of localization of the light at defects area beneath the surface of the film. Excitation and collection were at 780/390 nm for SHG study. j–l) To check the concept of subsurface defects contribution to this SHG signal, we have prepared and used a series of samples with subsurface SiO$_2$ and InP or GaAs ART pattern. The linear optical study (j) did not show any signature of these subsurface structures while dominated by topography (k). SHPM optical study (l) resolve the stripe pattern. The inset picture in topography plot (k) is the SEM image of the ART sample. SHG intensities are normalized (g)–(l) for comparison.
This leads to scattering and localization of light electric fields by scattering sites and creates patterns of sub-micrometer hotspots (Figure 3c) outside (and as well inside) the III–V film due to interference which resemble the observed SHPM plots. A lower density of scattering sites (Figure 3b) yields broader hotspots than a higher density, as observed in experiments. We have applied the SHPM to a wide variety of III–V epitaxial films, with surface defect densities \( n_d \) (dislocation defect densities-estimated from STEM images at surfaces of the films) ranging from \( 10^7 \) to \( 10^{10} \) cm\(^{-2} \). A global trend, illustrated by the data in Figure 4, is that higher defect density yields more densely packed hotspots. The left columns show SHPM scans, and representative profile cuts, of GaAs-Ge-off axis (Figure 4a), GaAs-Si-off axis (Figure 4b) GaAs-Si-on axis (Figure 4c) and In\(_{30}\)Ga\(_{70}\)As-GaAs (Figure 4d). The right column shows corresponding cross STEM, in which TDs appear as white streaks. Main plot (Figure 4e) shows average FWHM of SHG hotspots versus \( n_d \). Over the range \( 10^7 < n_d < 10^{10} \) cm\(^{-2} \), hotspot size scales roughly logarithmically with \( n_d \); a three-decade increase in \( n_d \) reduces SHG spot size by a factor of three. The trend is robust over a wide range of material systems. The characteristic length (hotspots separation) of sample with dense dislocation density (Figure 4c) is much shorter comparing to sample with lower defect density (Figure 4a).

Mean free path for photons is the average distance travelled between collisions at scattering sites. Measuring this characteristic length helps us to assess the Ioffe–Regel localization condition. We have used the recorded size of SHG hotspots in 2D as localization length by fitting an exponential function to these optical spots and later extract the optical mean free path from this. Multiple scattering and interference of the optical and electronics waves by random disorder (here dislocation defects) alter the eigenstate from being extended to localized state.[11,13,23,33,34] Optical mean free path can be extracted from

\[
R_{\text{localization}} = \frac{\hbar c}{2 \pi k e^{2 k L}}
\]

where \( R \) is wave localization length, \( L \) is mean free path, and \( k \) is wavenumber.[34] Figure 4f shows the theoretically extracted optical mean free path for all measured film with variety defects density versus optical localization length (size of the hotspots). The extracted mean free paths are comparable to the average distance between dislocation defects sites in the whole film estimated from cross STEM images of the samples. As an example, in case of GaAs-Ge on axis sample the extracted theoretical optical mean free path is 29 nm while the average distance between dislocations in the whole film is 37 nm. This distance only at the surface of the sample with much lower defect density is 626 nm. Figure 4f shows clearly that mean free paths are much smaller than optical wavelength thus satisfying the Ioffe–Regel localization condition. Larger the density of dislocations results in smaller localization length (optical hotspots size) thus smaller mean free path. A description of the localization length and mean free path estimation and calculation is included in Section S8 of the Supporting Information.

The In\(_{30}\)Ga\(_{70}\)As-GaAs samples (Figure 4d) illustrate an extreme example of a film with such high \( n_d \), that our system did not resolve any SHG features. Thus, \( n_d \approx 10^{10} \) cm\(^{-2} \) appears to be an upper limit. We learned from the simulation data that extreme dislocation density with a gap below \( \approx 20 \) nm between the defects (like this In\(_{30}\)Ga\(_{70}\)As-GaAs sample) would block light from entering the film. Simulation (Figure S9, Supporting Information) shows the random dense dislocation defects block the light from penetrating into the film. In addition, we studied...
the size and intensity of the hotspot in a GaAs-Si film as function depth of the film while sputtering the film. Experimental data (Figure S10, Supporting Information) shows that the size and intensity of hotspots decrease as we reach the area with higher defect density close to GaAs-Si interface. This confirms our observation and simulation results that high density of dislocations effectively prevent light from penetrating inside the film.

SHPM patterns were not only sensitive to defect density but also to defects orientation. To illustrate this, we compared SHPM patterns of InGaAs-InP–GaAs-Si structures grown with and without a Tellurium (Te) surfactant, which served to relax strain within the InGaAs layer during growth. STEM image (Figure S11a, Supporting Information) shows that dislocations within InGaAs layers grown with surfactant were along surface normal and yielded streaked SHPM patterns. Less relaxed InGaAs films grown with no surfactant, on the other hand, featured crossed and tilted dislocations as it shown in STEM images (Figure S11b, Supporting Information) and create localized looking hotspots as they appear in SHPM scan.

3. Conclusion

The ability to detect scattering and localization signatures of crystallographic dislocation defects address more details about the nature of light localization and offer an alternative path to light localization compared to super-resolution imaging and plasmonics. By using a nonlinear optical approach and high resolution apparatus we were able to clearly detect signatures of atomic-scale dislocation defects. This includes a bench-top technique that screens heteroepitaxial films for subsurface dislocations, and provides qualitative indicators of defect density, orientation, and arrangement. Since it requires neither sample preparation nor contact, this approach could help guide the choice of defect-control strategies (e.g., surfactants, growth rate, substrate temperature) in situ and in real-time during thin-film crystal growth. Strategic choice of sub-bandgap wavelength, which ensures that the incident light penetrates the buried defect origin site, should expand the applicability of SHPM to a wide range of technologically important $\chi^{(2)}$ films, including all III–Vs, strained silicon, and ferroelectrics. Moreover, since the basic process relies on the localization of defect-scattered fundamental light, third-harmonic probe microscopy could potentially characterize defect-laden films with centrosymmetric crystal structure in the same way, thus expanding applicability of the technique beyond $\chi^{(2)}$ materials to virtually any type of semiconducting or insulating film.

4. Experimental and Theoretical Section

Experimental Method and Setup: SHG optical study of semiconductor thin film was performed by fiber based nonlinear nearfield scanning optical microscope (NSOM) system with 50 nm fiber aperture (Figure 1a schematic). This uncoated probe scanning approach was used to avoid...
and minimize any enhancement and perturbation of the electromagnetic field at probe area.[23] The probe was kept at ~20–30 nm above the sample with feedback loop system monitoring the amplitude of the scanning probe. 76 MHz laser with ~150 fs pulse width at ~780 nm was focused on area about 5–10 μm on the sample (not in scale in Figure 1) and collection was done at 390 nm. The incident excitation angle was ~45° with P polarization. The Sample got scanned by piezoelectric stage under the stationary probe. Fiber probe which support light only below 600 nm pick up the propagating SHG signal of III–V film at nearfield regime and signal get filtered for residue of fundamental light. Photomultiplier tube (PMT) sensitive only to photon at 200–700 nm nearfield regime and signal get filtered for residue of fundamental light. The nonlinear response of the GaAs-Si on axis film is typically ~10^13 times weaker than linear reflection of the film. Nonlinear scanning probe microscope system has advantages of having very high spatial resolution and being noise free by collecting the SHG signal away from the linear signal.

Study in the linear regime with excitation at 780 nm has a disadvantage of not being able to distinguish the very weak scattered and localized light which create those hotspots. If we use the probe microscopy to look at the same wavelength of excitation light, the reflection of the excitation light at the surface dominate all the intensity information and the weak scattered and localized light at subsurface dislocation area would not be distinguished. Instead of the linear study, if we look at the nonlinear response of the III-V film at 390nm, there would not be such a problem of dominating reflection light from surface of the sample as the only reflected and dominating signal at surface is 780 nm which is filtered. Then scattered and localized SHG light intensity can be distinguished from the film typical SHG background respond. This filtering approach is capable of distinguishing the very weak SHG scattered and localized hotspot at presence of dominating surface reflect. The high resolution of the scanning probe microscope was explore and confirm (Figures S3 and S4, Supporting Information).

Aperture—Aperture is defined to mean the low-curvature (almost flat) fiber tip end of ~50 nm diameter created by melting, pulling, and tapering that is seen in the image in Figure S4a in the Supporting Information. Prior experimental work[37,38] showed that such near-flat regions of uncoated fiber tips serve as the dominant conduits for incoming light, enabling resolution of tens of nanometer. Indeed the SHG probe microscopy scans of control samples possessing well-defined stripe pattern (sharp edge) demonstrate a spatial resolution of <30 nm for the probe tip used here (Figures S3 and S4, Supporting Information).

Sample Growth: Variety of III–V sample grown over Si and Ge substrate—The III-V film such as GaAs was grown on on-axis Si (001) by metal–organic chemical vapor deposition (MOCVD) technique using two-step growth approach. AIXTRON CRIUS-R MOCVD system was used for that purpose. Essential silicon wafer cleaning and hydrogen passivation was done by vapor HF and wet HF processes. To promote the formation of double steps on Si along <110> direction for prevention of antiphase domains, baking at high temperature (>800 °C) was performed. III-V films were grown by using trimethylindium (TMIn) and trimethylgallium (TMGa) as the group-III precursors, tertiarybutylarsine (TBA), tertiarybutylphosphine (TBP) as well as arsine (AsH3) and phosphine (PH3) as the group V precursors. To have charge neutrality along the interface and promote the growth of single domain GaAs, wafer surface was saturated with an arsenic monolayer by introducing TBA molecules in the reactor at low temperature (<450 °C). Two step growth was introduced by <20 nm GaAs LT nucleation layer at (<450 °C) by low V/III ratio with roughness <5 nm measured by AFM and SEM. A 500 nm thick GaAs was grown at ~600 °C by using AsH3 with high V/III ratio and growth rate of ~1.3 micrometer/h with ~0.6 nm roughness. Quality and defect density of the crystal was checked by a high-resolution X-ray diffraction (HRXRD) and cross and planar STEM later. Annealing had been performed at the end to improve the quality of the crystal at 750 °C.[39] Alternative III–V and SiO2 stripe pattern ART sample (flat surface)—An AIXTRON CRIUS-R MOCVD system was used to grow InP films on patterned 300 nm wafers. On-axis Si (001) wafers were used to fabricate experimental test structures. These structures were created by forming a 180 nm thick thermal SiO2 layer followed by photo lithography and dry etching of trenches in the oxide in the [110] direction. 65 nm wide trenches were opened in the oxide and spaced at 130 nm pitch. The dimension of the trenches along the [110] direction was 25.4 nm. Prior to the epitaxial growth of InP, the residual and native oxide at the bottom of the trenches was precleaved and removed by a vapor HF/NH3 process. For the growth of InP films, trimethylindium (TMIn) was used as the group-III precursor, and tertiarybutylphosphine (TBP) and phosphine (PH3) were used as the group V precursors. The growth was carried out at low pressure. A two-step growth approach was implemented, in which the first step aimed at depositing an InP seed layer at low temperature (below 425 °C) using TBP with a V/III ratio of 25, and the second step is needed to bulk fill the oxide trenches with InP at 600 °C and with a V/III ratio of 100 by utilizing PH3 precursor.

Numerical Calculation Section: COMSOL software was used to complete the numerical calculation of finite element analysis over electric field (and optical intensity study) inside and outside the III–V materials. Electromagnetic Wave Frequency Domain package was used to be able to calculate near-field details of electromagnetic fields in addition to far-field details. For Figure 3 P-Polarized 780 nm excitation field with incident angle of 45° was used over III–V materials and SHG 390 nm result is plotted. The fundamental and second harmonic frequency domains are coupled through polarization definitions using electric field components. ~1 × 10^{-22} F V^{-1} was used as nonlinear matrix element for GaAs. Scattering properties of dislocation defects were replicated by assigning metallic properties based on previous experimental and theoretical publication showing dislocations act as tarp area for electrons. Appropriate boundary condition has to be assigned. Second Harmonic Generation (SHG) signal is studied along with fundamental harmonics through electric field calculation. Optical intensity was calculated by squaring the averaged electric field for Figure S7 (Supporting Information) during the investigation of resolution power of 50 nm fiber probe. Simulation for blocking the incoming light by dense dislocation defects were done in fundamental harmonics in Figure S9 in the Supporting Information. All the plots display averaged electric fields (average over all directions) as scalar elements.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The University of Texas at Austin has a patent under the name of inventors F.S. and M.D. (patent application US16157765) based on the technique described and performed in this experiment for detection of crystallographic defects.
Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

light localization, scanning probe microscopy, subsurface light scattering, subwavelength optics, threading dislocations

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