We demonstrate that silicon-vacancy (SiV) centers in diamond can be used to efficiently generate coherent optical photons with excellent spectral properties. We show that these features are due to the inversion symmetry associated with SiV centers. The generation of indistinguishable single photons from separated emitters at 5 K is demonstrated in a Hong-Ou-Mandel interference experiment. Prospects for realizing efficient quantum network nodes using SiV centers are discussed.

The negatively charged SiV center in diamond consists of a silicon atom and a split vacancy, as shown in Fig. 1(a) [9,10]. The silicon atom is centered between two empty lattice sites, and this $D_{3d}$ geometry forms an inversion symmetric potential for the electronic orbitals [9]. Recent measurements [10,11] and first principle calculations [12] have contributed to a detailed understanding of the electronic structure of the SiV center. As shown in Fig. 1(b), the ground and excited states each consist of a fourfold degenerate manifold where two degenerate orbitals are occupied by an $S = 1/2$ particle [13]. At zero magnetic field, the degeneracy is partially lifted by the spin-orbit interaction. Each excited state has dipole transitions to the two ground states forming an optical $\Lambda$ system, resulting in the emission spectrum shown in Fig. 1(c). These four transitions comprise the zero-phonon line (ZPL), which contains more than 70% of the total fluorescence. Remarkably, as discussed below, the inversion symmetry

![Image](https://example.com/image.png)

FIG. 1 (color online). Electronic structure and optical transitions of the SiV center. (a) The center is aligned along a $\langle 111 \rangle$ axis of the diamond host crystal, with the silicon atom (Si) located in the middle of two empty lattice sites. The system has $D_{3d}$ symmetry which includes inversion symmetry. (b) The optical transition is between different parity states, $^2E_u$ and $^2E_g$. Spin orbit interaction ($\lambda^{SO} \sim 250$ GHz, $\lambda^{SO} \sim 50$ GHz) partially lifts the degeneracy giving rise to doublets in the ground and excited states. Transitions $A, B, C, D$ are all dipole allowed. (c) The emission spectrum measured using off-resonant excitation at 532 nm on a single SiV center at 4.5 K.
results in weak coupling of the ZPL transitions to charge fluctuations in the SiV environment. This leads to the absence of spectral diffusion [14] and a narrow inhomogeneous distribution [15].

To demonstrate coherent emission of indistinguishable single photons from separate SiV centers, we use a HOM interference experiment. The interference of two identical single photons impinging on a beam splitter results in perfect photon bunching, with a vanishing probability of detecting coincident photons at the two different output ports. In our experiments, two separate SiV centers, cooled to cryogenic temperatures, were excited using a two-port setup. Incoherent excitation at various angles to the SiV centers produced a diamond sample imaged by this technique in a region with the greatest site density, leading to a high background in any photon correlation experiments. In order to isolate single SiV centers and minimize background from other emitters [22], the laser was tuned to the edge of the inhomogeneous distribution (νi) in Fig. 3(b).

The time dynamics of g2(τ) were measured HOM visibility of

\[ g^2(0) = \frac{g^2(0) + g^2(\tau)}{2} = 0.72 \pm 0.05. \]

The time dynamics of g2(τ) is understood via independent measurements of the excited state lifetime, absorption line width, and detector timing response. Our model (solid curves, see the Supplemental Material [16]) is in excellent agreement with the measured time dynamics, showing that

FIG. 2 (color online). Schematic of the two-channel confocal microscope built for the HOM experiment. (a) Channels I and II were used to address different emitters separated by tens of micrometers in the same sample. A continuous-wave 532-nm laser was used for excitation, and fluorescence was collected in single-mode fibers on ZPL and PSB ports simultaneously. (b) Collected ZPL fluorescence from the two channels were directed onto a free-space 50:50 nonpolarizing beam splitter. Linear polarizers were used to control the polarization of the single photons varying their distinguishability. Etalons were used to filter transition C before detection. (c) Emission spectrum before (brown) and after the etalons (blue).
the emitters were spectrally stable throughout the 4-hour acquisition period. We find that the interference visibility, $\eta$, is limited by about equal contributions from detector timing response and background events.

We next turn to a discussion of the key properties of SiV centers which made the present observations possible. Despite uncertainty about the absolute quantum yield [14], the strong ZPL of SiV [23] means that photons are emitted at high rates into the optical transition of interest. Inhomogeneous broadening corresponded to only a few transition line widths (see the Supplemental Material [16]), and high spectral stability of the transitions has been observed in bulk diamond [14] and nanodiamonds [13]. Together with these observations, our work shows that the optical coherence properties of SiV centers can be superior to those of NV centers [7,24]. Some of this advantage can be understood to result from the inversion symmetry of SiV centers which reduces sensitivity to electric field. In addition, it is important to consider the effects of phonons (strain) resulting in homogeneous (inhomogeneous) broadening mechanisms.

![Graph](image_url)

**FIG. 4 (color online).** HOM interference experiment. The second-order intensity correlation function $g^2(\tau)$ is plotted for two cases: (i) pink data show the results for indistinguishable single photons with identical polarizations, $g^2(0) = 0.26 \pm 0.05$. The error bars denote shot noise estimates. (ii) Green data show the results when photons from one emitter are orthogonally polarized and hence distinguishable, $g^2(0) = 0.66 \pm 0.08$. The blue and brown solid lines represent our model using independently measured parameters, only fitting a single parameter for background events in both datasets.

The electronic orbitals of the SiV center are parity eigenstates due to the inversion symmetry of the defect. The optical transitions take place between states of different parity, $2E_g$ and $2E_u$, which differ in phase but have similar charge densities [12]. This small change in the electronic charge density results in the strong ZPL since optical excitations do not couple efficiently to local vibrations. The coherence of the optical transitions can also suffer from spectral diffusion, a time-dependent change in the optical transition frequencies that results in an increased line width. This effect is commonly observed for NV centers, where the dominant source of spectral diffusion has been shown to be from local electronic charge fluctuations [25]. These changes in the charge environment result in a fluctuating electric field at the emitter that reduces the coherence of the optical transitions via dc Stark shift [7,26]. The sensitivity of the optical transition frequencies to electric field fluctuations depends on the permanent electric dipole moments.
of the orbital states of the emitter. Since the electronic states of the SiV center have vanishing permanent electric dipole moments due to their inversion symmetry, the optical transitions are relatively insensitive to external electric fields. This protects the optical coherence from charge dynamics in the crystal, preventing spectral diffusion and narrowing the inhomogeneous distribution of transition frequencies.

Additional homogeneous and inhomogeneous broadening mechanisms are provided by phonons and strain. Displacements of atoms in the host crystal can affect the optical transitions in two different ways. Static distortions, or strain, may reduce the symmetry of the defect and change the energy splittings [15] [shown in Fig. 1(b)]. A variation in local strain contributes to the inhomogeneous distribution of the resonance frequencies [16]. Displacements of the atoms can also give rise to dynamic effects during an optical excitation cycle. Acoustic phonons have been shown to cause orbital relaxation between \( E_X \) and \( E_Y \) states for the NV center in diamond [27]. For SiV centers, a similar process can happen between excited state orbitals by absorption (\( \Gamma_{\text{ph}}^{\text{th}} \)) or emission (\( \Gamma_{\text{ph}}^{\text{th}} \)) of an acoustic phonon, as shown in Fig. 1(b). Populations in the upper and lower excited state branches follow a Boltzmann distribution confirming thermalization of orbital states by phonons [14,15]. At low temperatures (\( k_B T \ll \hbar \omega_0 \approx 250 \) GHz), spontaneous emission dominates over stimulated processes (\( \Gamma_{\text{ph}}^{\text{th}} \ll \Gamma_{\text{th}}^{\text{th}} \)). To obtain an optical transition isolated from the phonon bath, our experiments were performed at 4.5–5 K (≈100 GHz) using the lower excited state branch. At these temperatures, we estimate a thermal broadening on transition C of about 12 MHz [14].

Our observations establish the SiV center as an excellent source of indistinguishable single photons. A strong ZPL transition, narrow inhomogeneous distribution, and spectral stability combine to make it a promising platform for applications in the fields of quantum networks and long-distance quantum communication. In particular, it should be possible to integrate SiV centers inside nanophotonic cavities [6,28–31] while maintaining their spectral properties owing to their insensitivity to electric fields. This may allow the realization of GHz bandwidth deterministic single photon sources [32] and a broadband system for quantum nonlinear optics at the single-photon level [33]. The small inhomogeneous distribution also makes SiV centers promising candidates as sources of multiple indistinguishable photons for linear optics quantum computing [34]. Furthermore, the spin degree of freedom in the ground state [13] can potentially be utilized to store quantum information, allowing the use of SiV centers as quantum registers for quantum network applications [35]. Coupling to the \(^2\text{Si}\) nuclear spin via hyperfine interactions [36] might allow realization of long-lived quantum memories [2]. Beyond these specific applications, the symmetry arguments presented above suggest that inversion symmetry might play an important role in the identification of new centers with suitable properties for quantum information science and technology [37].

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[16] See the Supplemental Material, which includes Refs. 17–21, at http://link.aps.org/supplemental/10.1103/PhysRevLett.113.113602 for more information on the sample, the inhomogeneous distribution, and the model used for the HOM experiment.


