Flying photonic qubits are particularly interesting for quantum communication since the photon coherence can be preserved over several kilometers. Photons are thus ideal particles for the implementation of quantum functionalities such as entanglement, non-localization and teleportation. The technical challenges associated with the manipulation of photonic states are, however, formidable due to the difficulty of bringing two photons into interaction within a short distance. Opto-electronic excitations in the solid state are, in contrast, much easier to manipulate. Here, the most promising candidates are flying opto-electronic qubits, which can be used for the exchange of quantum information between remote sites. Recently, flying qubits based on hybrid surface acoustic wave (SAW) structures on semiconductor platforms are attracting increasing attention. One prominent advantage of SAWs is the ability to provide mobile strain and piezoelectric potentials to modulate, confine, and transfer particles between remote on-chip locations. Researchers have coupled SAWs to a variety of systems, including, for example, electrons, superconducting qubits, diamond NV centers, and excitons. SAWs of μm-sized wavelengths have also been used to populate two-level systems with charged carriers as well as to induce the emission of anti-bunched photons at microwave frequencies.

Flying excitons with their natural inter-conversion to photons offer several advantages for opto-electronic control as well as for interfacing electronic and photonic excitations. Especially suitable for these applications are the long-living spatially indirect (or dipolar) excitons (IXs) in a double quantum well (DQW) structure subjected to a transverse electric field $\mathbf{E}_z$ [cf. Fig. 1(a)]. These excitons are formed by the Coulomb binding of electrons and holes driven to different quantum wells (QWs) by the applied field, which controls both the lifetime and the emission energy of the IXs via the quantum confined Stark effect. Analogously to the piezoelectric transport of charged particles, the charge-neutral IXs can be confined and transported by the mobile band-gap modulation produced by the SAW strain field, as illustrated in Figs. 1(b) and 1(c). The long-range transport of IXs enabled by their long lifetime has so far only been demonstrated in wide transport channels using SAWs with wavelengths of a few μm.

A main challenge for the implementation of flying excitonic qubits is the creation of two-level excitonic states interconnected by a transport channel, which can store single particles and convert them to photons. In this work, we realize a major step towards this goal by demonstrating the manipulation and remote pumping of two-level excitonic states by flying IXs propelled by GHz-SAWs in a GaAs-based semiconductor platform. The single states used here consist of excitons bound to single shallow impurities (denoted as $D_B$) in a DQW structure. We have recently reported that these states can be spatially isolated and resonantly excited by appropriately biasing the DQW structure. We demonstrate the pumping of individual $D_B$ centers by IXs driven along a narrow transport channel by a SAW. The oscillating SAW strain field modulates the narrow emission lines of the $D_B$ centers, which can be used as a sensitive probe of the local strain amplitudes. Time-resolved spectroscopic studies show that the recombination lifetime of the $D_B$ states is sufficiently short to follow the 3.5 GHz SAW pumping rate. More importantly, photon correlation investigations reveal that the acoustic pumping of these centers is followed by the emission of anti-bunched photons with a repetition rate corresponding to the SAW frequency, which shows that the center acts as a single photon source operating at very high frequencies.
FIG. 1. Acoustic manipulations and transport of indirect excitons (IXs). (a) IX formation via the dissociation of direct excitons (DXs) or trions (Ts) by the electric field \( F_z \) induced electron tunneling between the quantum wells (QWs) of a double quantum well (DQW). Within a narrow field range \( \sim 1 \text{kV/cm} \), the trion dissociation into IXs (dashed circles) is blocked leading to the selective excitation of bound exciton states (\( D_B \)). (Dissociation of a DX is also possible but less favorable energetically.) (b) Sketch of the samples for acoustic IX transport. The IX are formed in the DQW regions underneath a stripe-like semitransparent gate subjected to a bias \( V_t \), which enables both electrical control and optical access to the DQW. The stripes ends in a small circular trap area with a guard gate biased by \( V_g \). An interdigitated acoustic transducer (IDT) launches a SAW, which captures and transports the optically excited IXs along the stripe. The IX distribution is probed by collecting the spatially resolved photoluminescence (PL) along the path.

RESULTS

Exciton energy modulation by SAWs

The \( D_B \) center can be resonantly activated under weak optical excitation by biasing the DQW structure with a voltage \( V_t \) close to the onset of IX formation \[19\]. Under these conditions, the photoexcited electron-hole pairs bind to free residual carriers to form trions (Ts). The conversion of trions to IXs via electron tunneling through the DQW barrier requires the excitation of a free electron to the band states. As illustrated in Fig. 1(a) the tunneling to single \( D_B \) becomes energetically favorable to the IX formation. The emission from these centers is characterized by a narrow line [with full-width-at-half-maximum (FWHM) of 0.25 meV, cf. lowest spectrum in Figure 2(a)] spectrally isolated from the IX and direct exciton (DX, excitons whose electron and hole reside in the same QW) transitions.

The spectroscopic studies were carried out using the setup of Figs. 1(b) and 1(c) using SAWs with a wavelength of \( \lambda_{\text{SAW}} = 800 \text{ nm} \) (corresponding to a frequency of \( f_{\text{SAW}} = 3.58 \text{ GHz} \)). The photoluminescence (PL) spectra of Fig. 2(a) show that under an increasing SAW field the \( D_B \) line initially broadens and eventually splits into two. The SAW strain field periodically modulates the excitonic transition energies \( E_C(t) \) (\( C = \text{DX, T, } D_B \)) according to:

\[
E_C(t) = E_{C,0} + \frac{\Delta E_C}{2} \sin \left( \frac{2\pi}{T_{\text{SAW}}} t \right),
\]

where \( \Delta E_C \) is the peak-to-peak modulation amplitude and \( T_{\text{SAW}} = 1/f_{\text{SAW}} \) the SAW period.

For energy shifts \( \Delta E_C \) smaller than the linewidth, the modulation manifests itself as an apparent broadening of the time-integrated PL lines. For larger modulation amplitudes, the time-averaged PL develops a camel-like shape with peaks at energies \( E_{C,0} \pm \Delta E_C/2 \) corresponding to the maximum and minimum band-gaps under the SAW field, thus reproducing the behavior observed in Fig. 2(a). Figure 2(b) displays the dependence of the peak-to-peak modulation amplitude for the \( D_B \) (\( \Delta E_B \)) and DX (\( \Delta E_{\text{DX}} \)) transitions determined from fits of the measured spectra to a model for the time-integrated PL line shape under a SAW described in detail in Sec. SM2.

The dashed line yields the corresponding strain-induced band-gap modulation determined using the GaAs deformation potentials and the SAW fields in the DQW calculated from the applied rf-power (cf. Sec. SM1). As expected for a shallow center, the \( D_B \) energy modula-
A quantitative determination of very small strain levels. It is worthwhile to emphasize that narrow laser spot at the static stripe gates under optical excitation by a focusing along the direction. The acoustic field pushes the IXs upwards leading to a strong increase of the IX emission of a DB center located about 13 µm (corresponding to 16λSAW) away from the excitation spot (dashed circle).

**Long-range IX transport**

The lower panel of Fig. 3(a) displays a spectrally resolved PL map of the exciton distribution under the electrostatic stripe gates under optical excitation by a focused laser spot at y = 0 [cf. sketch of Fig. 3(e)]. This map was recorded in the absence of a SAW under a transverse field $F_z = 5$ kV/cm across the DQW. The PL around the excitation spot (thin blue line in the upper panel, integrated for $|y| < 3$ µm) shows the characteristic emission line from DX, T, and IXs superimposed on a broad PL background from the doped layers and emission centers in the substrate (note that the intensity of the DX and T lines become strongly suppressed under the applied transverse field). Away from the generation area the PL becomes dominated by the emission from IXs, which, due to the long recombination lifetime, can diffuse up to the top region of the guard gate (thick orange line). In fact, most of the remote PL from DXs and Ts arises not from the diffusion of these species but rather from the conversion of diffusing IXs to DXs or Ts. Note also that the diffusing IXs can easily cross the narrow gap between the stripe and guard gate at y = 13 µm.

Figure 3(b) displays a PL map recorded under the same conditions as in Fig. 3(a), but now under a SAW propagating along the y direction. The acoustic field pushes the IXs upwards leading to a strong increase of the IX PL for positive y (cf. orange line in the upper panel) and a reduction for negative y. The recombination energy and location of the transported IXs can be controlled by changing the bias applied to the gates. As an example, Fig. 3(c) shows a map recorded by increasing the guard bias by 0.08 V relative to $V_t$. The IX emission energy blueshifts as IXs enter the guard gate as well as when the particles are pushed by the SAW beyond the guard, where they become converted to DXs or trions. The additional energy for the blueshift is provided by the moving SAW field.

The IX transport over tens of $λSAW$ can remotely activate DB, as shown in Fig. 3(d). Here, the SAW amplitude and gate biasing conditions were selected to enhance the emission of a DB center under the guard gate approx. 13 µm (corresponding to 16$λSAW$) away from the excitation spot (dashed circle).

**Photoluminescence dynamics and autocorrelation**

The excitation of the DB centers by GHz SAW fields induces a strong time modulation of their optical emission. The red line in Fig. 3(a) displays the time-resolved PL trace of a center recorded on a DB center located about $l \sim 8$ µm away from the laser excitation spot. The blue curve reproduces, for comparison, a time-resolved profile of the exciting laser spot (not to scale), which consists of pulses with a FWHM of about 0.28 ns and a repetition time of 9 ns. The short-period oscillations in the DB response (red curve) correspond to the SAW period $T_{SAW} = 0.28$ ns. A close up of the oscillations (upper inset) reveals that the DB emission decays with a time constant of approx. 110 ps, thus demonstrating that the PL from these centers can follow the fast varying acoustic field. The pulses create a high density cloud of IX, which partially screen the modulation potential around...
FIG. 3. Optically detected acoustic transport of IXs. (Lower panels) Spatially resolved photoluminescence maps on a log intensity scale in the absence (a) and in the presence of a SAW for (b) $P_{\text{rf}} = -9$ dBm and $V_t = V_g = 0.2$ V and (c) $P_{\text{rf}} = -11$ dBm, for $V_t = 0.23$ V, and $V_g = 0.31$ V. (d) Corresponding map with an impurity center $D_B$ on the transport path and biasing conditions to enhance the impurity PL ($P_{\text{rf}} = -14$ dBm and $V_t = V_g = 0.4$ V). (d) Sketch of the transport path defined by electrostatic gates. The upper panels in (a)-(d) display profiles of the PL intensity integrated around the excitation region ($|y| < 3 \mu$m) and along the transport path ($y > 3 \mu$m).

The photon emission statistics of the $D_B$ centers was addressed by recording photon autocorrelation ($g^2$) histograms under acoustic excitation using a Hanbury-Brown and Twiss setup. The results obtained after correcting the background emission from IX states (see details of the data treatment in Sec. SM3) are shown in Fig. 4(b). As in Fig. 4(a) the short and long period oscillations are associated with the repetition periods of the SAW and the laser pulses, respectively. The histogram shows a clear suppression of the coincidence rate at the time delay $\tau_c = 0$. In order to confirm the selective suppression at $\tau_c = 0$, the inset displays the averaged value $\bar{g}^2(\tau_c)$ for $g^2(\tau_c)$ over a time interval of 0.64 ns around time delays multiple of the laser repetition period. The latter shows that the suppression of coincidences at $\tau_c = 0$ is well below the statistical fluctuations, thus proving the emission of anti-bunched photons. The autocorrelation $g^2(0) = 0.75 \pm 0.03$, which corresponds to the simultaneous emission of 4 photons, is probably an upper limit determined by photon collection from the neighboring areas from the center.

**DISCUSSION**

In conclusion, we have investigated the dynamic modulation and transport of excitons by high-frequency, sub-micron-wavelength SAWs on GaAs DQW structures. In particular, we show that GHz-SAW field can pump single exciton states bound to impurities, which act as two...
level states emitting anti-bunched photons. The centers can follow the high-frequency acoustic pumping rate leading to the emission of anti-bunched photons synchronized with the SAW phase. The results thus demonstrate the feasibility of exciton manipulation as well as of exciton-based GHz single-photon sources using acoustic waves. Finally, multiple single exciton states can be excited by a single SAW beam, thus providing a pathway for scalable arrays of synchronized single-photon emitters.

**METHODS**

**Sample structure:** The studies were carried out on an (Al,Ga)As DQW structure consisting of two coupled GaAs QWs grown by molecular beam epitaxy on a n-type doped GaAs(001) substrate [cf. Fig. 1(a)]. The QWs are 16 nm-wide and separated by a 4 nm-thick Al_{0.33}Ga_{0.67}As barrier. The electric field $F_z$ induced by the bias $V_i$ applied across the structure drives photoexcited electrons into QW$_2$ and holes into QW$_1$, thus increasing the recombination lifetime. Due to the narrow barrier width, the overlap of the electron and hole wavefunctions in the adjacent QWs is still sufficiently strong to maintain the Coulomb correlation required for IX formation. The DQW structure can thus hold both direct (or intra-QW, DX) and indirect (inter QW) excitons with transition energies indicated by the brown and green arrows in Fig. 1(a), respectively.

**Generation of SAWs:** SAWs with a wavelength of $\lambda_{\text{SAW}} = 800$ nm (corresponding to a SAW frequency $f_{\text{SAW}} = 3.58$ GHz at 4 K) were generated by split-finger aluminum interdigital transducers (IDTs) deposited on the sample surface [cf. Fig. 1(b)]. The depth of the DQW was chosen to yield a type II modulation under the SAW excitation. The IDTs are oriented along a $\langle 110 \rangle$ surface direction with a length and width of 150 $\mu$m and 28 $\mu$m, respectively. The SAW intensity is quantified in terms of either the nominal radio-frequency (rf) power applied to the IDT ($P_{\text{rf}}$) or the SAW linear power density $P_{\text{L}}$, which is defined as the ratio between the acoustic power and the width of the SAW beam. The latter is obtained by using the measured rf-scattering parameters of the IDTs to determine the fraction of the input rf-power coupled to the acoustic mode.

**Electrostatic channels for IX transport:** The IX acoustic transport channel is defined by a semitransparent Ti stripe placed on the SAW path and biased with a voltage $V_g$ with respect to the doped substrate (cf. cross-section diagram of Fig. 1). The stripe is 2 $\mu$m wide and ends on a small trap (diameter of 0.9 $\mu$m) surrounded by a guard gate with an external diameter of 7.5 $\mu$m. The guard gate, which is biased by a separate voltage $V_g$, reduces lateral stray electric fields in the narrow regions of the stripe, which can dissociate IXs [22]. As shown in the experiments, IX can easily tunnel over the small separation region (approx. 0.2 $\mu$m) between the stripe and guard gate.

**Optical spectroscopy:** Optically detected IX transport experiments were carried out at 4 K with a spatial resolution of approx. 1 $\mu$m. The excitons were excited by a spot from a pulsed laser (wavelength of 770 nm, pulse width of 280 ps) focused by a microscope objective on the semitransparent stripe. The photoluminescence (PL) from IXs emitted along the transport path is collected by the same objective and spectrally analysed by a monochromator with a charge-coupled-device (CCD) detector. Spatially and spectrally resolved PL maps of the IX distribution are obtained by aligning the trans-
port path with the input slit of the spectrometer. The
time-resolved PL studies were performed by triggering
the laser pulses at a subharmonic \( f_{\text{SAW}/32} \) of the rf-
frequency applied to the IDTs. The PL was in this case
spectrally filtered by a band-pass filter and detected by a
superconducting photon detector coupled to a time cor-
relator with a combined time resolution of 40 ps.

Authors contributions: M.Y., P.V.S., and C.B. have con-
ceived this project. M.Y. and P.V.S. have carried out the
optical and electrical measurements and analyzed the
data. K.B. designed and fabricated the layer structures
using molecular beam epitaxy. M.Y. and S. T. have fabri-
cated the acoustic devices. M.Y. and P.V.S. have equally
contributed to the analysis of the results as well as to the
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SUPPLEMENTARY MATERIAL

Remotely activated GHz anti-bunched photon source from single exciton states

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SM1. CALCULATION OF THE SAW-INDUCED ENERGY MODULATION

We calculate in this section the bandgap modulation induced by the SAW modulation. For that purpose, we compare the measured electrical response of the IDTs with numerical calculation of the SAW fields carried out by solving the elasticity equations for the layer structure of the sample \cite{16}. Fig. SM1 displays the rf scattering coefficient $S_{11}$ measured for the IDT, which yields the fraction of the applied rf power reflected by the transducers. From the amplitude of the dip at the resonance frequency $f_{\text{SAW}} = 3.54$ GHz, we extract that for a typical applied power of 30 W/m, the transmitted SAW power propagating along one direction of the IDT is $P_\ell = 0.4$ W/m. The SAW strain modulates the energy of both the conduction, $E_e$ and the valence bands (heavy hole), $E_{hh}$. The calculated combined bandgap modulation $E_e - E_{hh}$ at the depth of the DQW is shown in Fig. SM2(a). We plot in Fig. SM2(b) the calculated piezoelectric field $E_p$ in the DQW plane underneath the metal gates. For high SAW amplitudes, this field can dissociate excitons, thus inducing a quenching of the PL.

![FIG. SM1. Radio-frequency scattering parameter $S_{11}$ (corresponding to the electric reflection coefficient) measured at room temperature for the IDT used to generate the SAWs in the experiments.](image1)

![FIG. SM2. (a) Calculated bandgap strain-induced modulation $E_e - E_{hh}$ at the depth of the DQW calculated for $P_\ell = 0.4$ W/m. (b) The corresponding piezoelectric field $E_p$.](image2)
SM2. ACOUSTIC MODULATION OF THE TRANSITION ENERGIES

In addition to the studies of the dependency of the bound exciton linewidths on acoustic intensity, we also investigated how the acoustic fields impact the DX and trion lines. Figure SM3(a) displays PL spectra recorded under flat-band conditions for increasing SAW intensities (quantified by the nominal power $P_f$ applied to the IDT). Each spectrum displays two lines associated with the excitation of DXs and trions ($T$, a DX bound to a free carrier, studied in Ref [19]). The spectrum for the lowest $P_f$ essentially corresponds to the PL response in the absence of acoustic excitation. With increasing SAW intensity, both lines slightly broaden and the overall emission intensity decreases.

In order to extract the effects of the acoustic field, we assume that PL lines have a Gaussian shape with width $w$ and that their central energy is modulated by the SAW according to Eq. 1 of the main text. Under these assumptions, the time-integrated PL spectrum can be expressed by the following integral over one SAW period

$$I_C(E) = \frac{1}{T_{SAW}} I_{C,0} \int_{0}^{T_{SAW}} \exp \left[ -2 \left( \frac{E - E_C(t)}{w} \right)^2 \right] dt.$$ (SM1)

For energy shifts $\Delta E_C << w$, the modulation manifests itself as a broadening of the lines with increasing SAW amplitude. For high modulation amplitudes, the time-averaged PL line splits into two peaks with energies $E_{C,0} \pm \Delta E_C/2$ corresponding to the maximum and minimum band-gaps under the SAW field.

The lines superimposed on Fig. SM3(a) are fits of the measured PL data to Eq. SM1. From the fit we extract the SAW modulation amplitudes $\Delta E_C$ for DX and trion, plotted as symbols in Fig. SM3(b) for different SAW amplitudes. The latter is quantized in terms of the SAW linear power density $P_f$, defined as the acoustic power carried by the SAW mode per unit length perpendicular to the SAW beam. The expected linear dependence on $\sqrt{P_f}$ is revealed when the SAW-induced apparent broadening exceeds the unperturbed (i.e., in the absence of a SAW) width of the PL line, as shown by the dashed lines. For $P_f^{1/2} > 0.7$ (W/m$^{1/2}$) one observes a nonlinear increase of $\Delta E_C$ with SAW amplitude.

The modulation amplitude determined from the fits for DX (square) correlates well with the band-gap modulation expected from the deformation potential mechanism shown in Fig. SM1. As an example, the circled red cross in Fig. SM3(b) marks $\Delta E_C$ for $P_f = 0.4$ W/m extracted from the measured data, which is in good agreement with the analysis shown in Fig. SM2(a). In contrast, $\Delta E_C$ for trion (circle) deviates significantly from the calculation. It indicates that the simple model of adding the respective modulation of the conduction band and the valance band, used for the calculation here, is not suitable for trion due to the binding to an extra charge.

SM3. BACKGROUND CORRECTION OF THE AUTOCORRELATION DATA

Due to their long lifetimes, IX can diffuse and accumulate around the $D_B$ centers. As a result, IX emission is also present within the spectral window of the autocorrelation measurements. The repopulation time of the IX around the $D_B$ center is very long: as a consequence, the SAW modulation of IX intensity in the measured $g^{(2)}$ can be ignored. To correct for the background emission from IXs, we diverted the detection spot away from the $D_B$ center to a position, where the PL from the center disappeared but the IX signal remained similar. A background autocorrelation $[C_{bgd}]^2$...
was recorded at this position. The measured total autocorrelation $[C_{\text{total}}]^2$ can be expressed as $[C_{\text{bgd}} + C_{\text{center}}]^2$, where $[C_{\text{center}}]^2$ is the autocorrelation from the DB center that is sought after. From the measurements we extract $[C_{\text{bgd}}]^2 + 2C_{\text{bgd}}C_{\text{center}} \approx 0.85[C_{\text{total}}]^2$. We fit the measured $g^{(2)}$ to a smooth (i.e., without SAW induced oscillations) multi-peak profile (Lorentzian), each peak sharing the same height and width, and use this profile to approximate $[C_{\text{total}}]^2$. Finally $0.85[C_{\text{total}}]^2$ is subtracted from the measured $g^{(2)}$. 