Cathodoluminescence visualisation of local thickness variations of GaAs/AlGaAs quantum-well tubes on nanowires

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Abstract

We present spatially and spectrally resolved emission from nanowires with a thin radial layer of GaAs embedded in AlGaAs barriers, grown radially around taper-free GaAs cores. The GaAs layers are thin enough to show quantization, and are quantum wells. Due to their shape, they are referred to as quantum well tubes (QWTs). We have investigated three different nominal QWT thicknesses: 1.5, 2.0, and 6.0 nm. They all show average emission spectra from the QWT with an energy spread corresponding to a thickness variation of $\pm 30\%$. We observe no thickness gradient along the length of the nanowires. Individual NWs show a number of peaks, corresponding to different QW thicknesses. Apart from the thinnest QWT, the integrated emission from the QWTs shows homogeneous emission intensity along the NW. The thinnest QWTs show patchy emission patterns due to the incomplete coverage of the QWT. We observe a few NWs with larger diameters. The QWTs in these NWs show spatially resolved variations across the NW. An increase in the local thickness of the QWT at the corners blocks the diffusion of carriers from facet to facet, thereby enabling us to visualise the thickness variations of the radial quantum wells.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Semiconductor nanowires (NWs) have potential applications in a range of devices including light emitting diodes [1–3], lasers [4–6] and solar cells [7, 8]. NWs have a large surface-to-volume ratio and can be used to increase the surface area compared with a two-dimensional substrate. This is especially...
the case for NWs covered with a radial quantum well (QW), where the total area of the QW can exceed that of the substrate surface. Their shape means that these radial QWs are referred to as quantum-well tubes (QWTs) [9]. Due to the ability of the NWs to accommodate strain, it is possible to grow defect free heterostructures that are difficult to achieve with planar growth and QWTs have been grown in several III–V and III-Nitride semiconductor material systems, namely InGaAs/InP [3], InGaAs/GaAs [10], GaAs/AlGaAs [9, 11–13], GaAs/GaAsP [14], GaInP/GaP [15] and InGaN/GaN [16]. NWs with QWTs have some specific applications, in particular as lasers where the high gain of the QWs can reduce the threshold [5, 17–21]. Furthermore, the inclusion of one or more QWTs gives the freedom to choose the emission wavelength by changing e.g. the composition [10] or the thickness [17] of the QW. It is also possible to create a Fabry–Pérot cavity along the length [22] of the NW to decouple the optical cavity from the QW, which eliminates reabsorption [21]. Other potential applications are photodetectors [23] and modulation doping of the QWT for transport devices [24].

In this paper, ‘NW’ is used to refer to the whole structure, whereas ‘QWT’ refers specifically to the QW either the structure or the emission, and there is a QWT in the NW. The NWs in this study were grown by metalorganic chemical vapour deposition on (111)B-oriented GaAs substrates with the GaAs core grown using the two-temperature procedure described in [25] and with 50 nm Au nanoparticles as catalyst. The growth was initiated at 450 °C and the main part of the core was grown at 375 °C. This procedure leads to a pure zinc blende crystal structure, virtually free from twin defects, stacking faults or wurtzite segments. The NW diameters have very little tapering over several µm, and adopt 110 side facets when the temperature is ramped up to 750 °C for the radial growth of AlGaAs/GaAs/AlGaAs QWT [26]. The core was covered by a 90 nm thick AlGaAs shell, grown at 750 °C. After the first AlGaAs shell, a single thin GaAs layer was grown to serve as a QWT. Samples with nominal QWT thicknesses of 1.5, 2.0 and 6.0 nm in the radial direction were grown by adjusting the growth time of the radial GaAs layer. The GaAs QWT was covered by a second 25 nm thick AlGaAs shell. Both AlGaAs barriers have an Al content of about 40–45%. To prevent oxidation of the AlGaAs, the NWs were finally capped by a 90 nm thick AlGaAs shell. Details about the growth can be found in [9].

The cross-sectional transmission electron microscopy (TEM) samples were prepared by embedding in a resin and microtoming. TEM was carried out in a JEOI 2100 F instrument using 200 keV beam at the Australian National University (ANU). Aberration corrected scanning transmission electron microscopy was carried out on an FEI Company Titan 80 – 300 field emission gun transmission electron microscope fitted with aberration correctors (CEOS GmbH) on both the probe and image forming lens systems with a 300 keV beam at the Monash Centre for Electron Microscopy (MCEM).

Figure 1 is an overview of the structure of the NWs with a nominal 2.0 nm QWT. Figure 1(b) is a TEM image of a typical NW in side view, and figure 1(a) shows a high-angle annular dark-field scanning TEM (HAADF-STEM) image showing a cross-sectional view of the NW. The QWT structure has a hexagonal cross-section with predominantly 110 facets. HAADF imaging is highly sensitive to Z contrast and delineates the different regions as follows. From the centre, there is the GaAs nanowire core, followed by an AlGaAs barrier, a thin GaAs QWT, and an outer AlGaAs barrier followed by a final GaAs cap. The structure has a three-fold symmetry clearly exhibited by a difference in the QW thickness at the 112 corners, notably thicker at the 112A corners and thinner at the 112B corners. Figure 1(c) is a high-resolution image of the top part of the cross-section as indicated by the white rectangle in (a) and clearly illustrate the difference in the QW thickness. In addition, a non-homogeneous AlGaAs shell is also visible in figure 1(a) where dark contrast radial bands are visible along the 112 directions. Zheng et al [27], clearly show a polarity driven three-fold symmetry in the AlGaAs barrier with thick and thin Al rich bands in the AlGaAs along the 112 B and A directions respectively. The geometry of the QWT can lead to different emission energies both along the NW and from facet to facet [28]. More TEM images of these structures can be found in references [9, 27, 29, 30], especially [29] shows TEM images of the QWTs used in this study.

Since one of the most important applications of QWTs in NWs is lasers, there are many reports on optical properties of NWs containing QWTs, either ensembles [12, 15, 19] or single NWs [5, 10, 17, 22]. These studies only reveal the average properties of the QWTs, and spatial resolution is needed to understand how the QWT emission varies along the NW. This has been done with either micro-photoluminescence [9, 28–30] (µPL) or cathodoluminescence (CL), using scanning electron microscopy [31] (SEM) or TEM [32].

To study the emission from the QWTs, we have used CL imaging and spectroscopy in an SEM. One of the most powerful data-collection modes is hyperspectral imaging, where each pixel of the image contains a full spectrum, resulting in a data cube (x, y, λ and intensity). This was first introduced in 1987 by Bimberg et al. [33] and has since become a standard recording mode in CL. Typically, an acceleration voltage of 5 kV and a probe current of 10–100 pA were used. In order to achieve a high spectral resolution and to avoid thermal broadening, the studies were performed at liquid helium temperatures, 10 K. In order to get overviews of the QWTs, the NWs were analysed as grown on the substrates in side view, on freshly cleaved substrates. The fresh cleave ensures that there is limited structural damage to edge from handling the sample. The NWs were also transferred onto Si substrates to study single QWTs. A GaAs photomultiplier tube (PMT) was used for single wavelength (monochromatic) spectral imaging, and a Si-CCD was used for hyperspectral imaging. For all the hyperspectral data presented here, a spectral resolution of about 2 meV was used. The combination of probe current and detection parameters was chosen to achieve both spatial and spectral resolution with an optimised combination of recording time, sample drift and signal-to-noise ratio of the emission. The monochromatic images are presented in grey scale, the maximum intensity is white and no signal is black. The hyperspectral images are presented with a colour scale going from blue-green-yellow-orange-red, where blue is no signal to the maximum intensity of red.
2. Results

2.1. Single wire spectra and QW quantization

It is important to study the homogeneity of the QWTs, especially if they are to be used as light emitters. Unless they emit at the designated energy, light-emitting diodes will have an undefined colour. For lasers, it is even more important to have a homogeneous QWT, as only QWTs with the right energy will contribute to the lasing. It is also interesting to study the growth of the QWTs from a fundamental point of view. Ensembles and single NWs of all three QWT thicknesses were studied and as expected, the energy of the peak emission increases as the nominal QWT thickness is reduced. This blue shift is a result of increased quantization as the QWT thickness is reduced. This is in line with previous studies of samples in this series [29]. Figure 2(a) presents spectra from single QWTs showing typical emission of all three thicknesses. Each spectrum shows a broad peak with some fine structure. The spectra in figure 2(a) are normalized in order to illustrate the shape of the emission spectrum with different QWT thicknesses. However, the emission intensity from the thinnest QWT is significantly weaker than for the other two QWT thicknesses. This was confirmed by comparing the intensity with the core emission. Figure 2(b) shows theoretical values of the confined states as a function of the thickness of the QWT. The data has been adapted from [29]. These calculations were done for a circular geometry, rather than the actual hexagonal geometry. According to reference [9], the circular geometry is a good representation of the quantized states in the QWT. However, the calculations do not take any axial (along the NW) quantization into account, only radial quantization. Thickness fluctuations on a short scale can lead to quantum-dot-like energy states. For the thinner QWTs, only the ground state is confined and we only expect single emission peaks from QWTs with a thickness of less than 4.5 nm. Thicker QWTs have confined excited states as well, and it should be possible to observe emission from these states. For the three QWT thicknesses, the emission in figure 2(a) is centred at 1.62, 1.80 and 1.95 eV, corresponding to average QWT thicknesses of 5.5, 2.2 and 1.2 nm, respectively, according to the calculations in [29]. From [29], the thickness ranges in figure 2(a) are: 3.5–7.0 nm (nominally 6.0 nm QWT); 1.5–3.0 nm (nominally 2.0 nm QWT); and 0.7–1.4 nm (nominally 1.5 nm QWT). The apparent spread in thickness is therefore about a factor of two, or ±30 %, for all three QWT thicknesses.

According to the theoretical calculations in [29] we expect to be able to observe the ground state emission in the range 1.55 to 2.0 eV, and emission from the first excited state in the range 1.68 to 2.0 eV. Assuming that we always observe emission from the ground state, it is only when we observe ground state emission below 1.68 eV that we can potentially observe emission from excited states at higher energies. The emission observed at 1.70 eV on the high-energy side of the main emission from the 6.0 nm QWT could therefore be the
excited states of the corresponding ground state at 1.55 eV. If the 1.70 eV emission is associated with excited states, the spatial origin should coincide with the spatial origin of the ground state in monochromatic CL images at 1.55 eV. Alternatively, the 1.70 eV emission could originate from thinner areas of the QWT. The thinner QWTs (nominally 1.5 and 2.0 nm) only show emission above 1.70 eV, and the emission is therefore assigned exclusively to the ground state emission from thin QWT regions.

2.2. Side view CL-imaging

The spectrum from single or ensembles of NWs illustrates the varying thickness within a single QWT. In order to study how the QWT thicknesses are distributed along the individual NWs, we have studied all samples by recording a series of monochromatic images. For the imaging, we cleaved the sample and studied the NWs as grown in side view. This enables us to probe hundreds of NWs, and the regions on the substrate were chosen at random. Care was exercised to avoid the edges of the original substrate, as the growth might be different near the edges. Using this approach, we were able to extract, not only variations in the emission along the single NWs but also variations from QWT to QWT.

2.3. Hyperspectral imaging of a 1.5 mm QWT

We have used hyperspectral imaging to study the variations in intensity and spectral emission along individual NWs. This study was typically performed on at least ten different single NWs for each QWT thickness. Data from one of the NWs is presented in figure 4 for the thinnest QWT. For this study, the NWs were broken off and transferred to a Si substrate. The

Figure 3 shows a series of monochromatic images from the 1.5 nm thick QWT sample. Images recorded at three different energy windows are presented. Each energy window covers a range of QWT thicknesses. All images are normalised to the maximum intensity in the individual images, where black is zero and white is the maximum intensity. The images show bright spots with an extension of about 200–500 nm, along the NW lengths. The image recorded using the lower energy window (1.92 eV) in figure 3(a) shows fewer brighter spots compared with the other two energy windows, figures 3(b) and (c). The bright spots are distributed evenly along the NWs irrespective of the detection energy window. This suggests that there is no gradual thickness gradient along the length of each individual QWT. A further observation can be made by making a colour-composite image of the three energy windows (see figure 3(e)). 1.92 eV (red), 1.95 eV (green) and 1.98 eV (blue). The composite image shows mainly single colours, and very few spots show mixed colours or white. This suggests that the inhomogeneity in the emission observed along this NW with a nominal 1.5 nm QWT thickness arises from local QWT thickness variation. We find similar behaviour for all three QWT thicknesses, even if the thinnest QWT (nominally 1.5 nm) shows the least spatial overlap with the other two energy windows. This is in line with a previous study of GaAs QWTs in AlGaAs barriers using monochromatic CL imaging, showing some fluctuations in the emission energy along the length of NWs with QWTs [31].
orientation of the NW is confirmed by the fact that the outer AlGaAs barrier grows axially as well as radially. This axial growth rate is higher than the radial counterpart. This means that the last few hundred nm near the top is pure AlGaAs and does not show any emission in the QWT range or from the GaAs core. Figure 4(a) shows the SEM image of a single NW and figure 4(b) shows the integrated QWT emission in a panchromatic image, excluding the GaAs core emission. Figure 4(c) shows the spectrally and spatially resolved emission from the same QWT. The panchromatic image shows that the QWT is not continuous along this thin QWT, or at least the QWT is too thin to have any confined states. The bright spots appear to have an axial extension of 200 to 500 nm, which is most likely a measure of the diffusion of carriers, both in the barriers and the QWT itself. The spectral width is 3–10 meV, most likely limited by the 2 meV spectral resolution of the detection system. These states are a mixture of quantum well- and quantum dot-like emission from the QWT, where the sharper peaks are from the quantum dot-like structures. There is no trend in the QWT emission energy with position along the NW, which indicates that there is no gradient in the QWT thickness, confirming the observations of figure 3.

2.4. Hyperspectral imaging of a 2.0 nm QWT

We performed the same study of the emission from the 2.0 nm thick QWT sample. In contrast to the thinner QWT, the panchromatic image of this QWT reveals that the emission is quite homogenous along the length. When expanded into a hyperspectral map, it shows significantly more emission peaks than for the QWT in figure 4. As for the thinner QWT, there is no trend in the emission energy along the length, apart from an increase in the energy near the top. The individual peaks have an apparent spatial extension of 200–500 nm, like in the case of the thinner QWT. There is a clear spatial overlap between different emissions. Each pixel (40 by 40 nm$^2$) along the length appears to show five to ten separate emission peaks, some of them as narrow as 2 meV, which is the limit set by the spectral resolution of the set-up. As a comparison, samples from the same batch of 2.0 nm QWTs have µPL emission peaks with line widths of less than 1 meV [29]. As for the thinnest QWT, all emission is expected to be from the ground state, as we do not observe emission in the range below 1.68 eV.

To study the emission from the NW in figure 5, we recorded a series of hyperspectral images with increasing probe currents, from 20 to 1000 pA (a factor of 50). As expected, the emission intensity increases, though only sub-linearly by a factor of about 20. With the highest probe currents, the overall shape of the spectrum is maintained, with some broadening in the narrowest peaks in the spectrum by about a factor of 2. These narrow peaks have previously been attributed to localized quantum-dot like states in the QWT [29].

Figure 4. (a) SEM image and (b) corresponding panchromatic image of a single NW with a 1.5 nm thick QWT. (c) a hyperspectral map along the same QWT. The growth direction is from left to right in the images. The $x$-axis is the same in all images.

Figure 5. (a) SEM image and (b) corresponding panchromatic image of a single NW with a 2.0 nm thick QWT. (c) a hyperspectral map along the same QWT. The growth direction is from left to right in the images. The $x$-axis is the same in all images.
These narrow peaks are only visible at low temperatures, as their localization energy is less than the thermal energy \[30\]. With increasing excitation density, it could be possible to observe emission from excited states if they exist, as the ground state can be saturated. We do not observe any additional peaks in the spectrum even at the highest probe current. From the theoretical calculations presented in figure 2(b), we do not expect that this QWT has any excited QWT states. It is therefore not surprising that we do not observe any additional peaks, even at higher excitation density.

2.5. Hyperspectral imaging of 6.0 mm

The 6.0 nm QWT shows the same homogeneity in the panchromatic image as the 2.0 nm thick QWT. The hyperspectral image shows spectrally less well-defined emission than from the thinner QWTs. This can be attributed to the smaller energy spacing with thickness variations on the atomic scale and a closer lateral spacing of areas of different thicknesses. This leads to an overlap in the peak positions of the emission spectra from the individual segments of different thicknesses. A thicker QWT will also reduce the likelihood of quantum dot formation previously observed in the thinner QWTs. A local thickness variation will not create enough confinement to form a quantum dot. The peak width of the emission peaks appears to be broader, above 10 meV which is well above the spectral resolution of the collection system. From figure 2(b), the emission in the range of 1.55 to 1.65 eV is expected to originate from ground states that have bound excited states. This fits well with the range of the average emission from the 6.0 nm thick QWT in figure 2(a). To investigate possible emission from excited states, we have selected a segment near the top of the NW around the 3 µm position as indicated by a dashed box in figure 6(c), with emissions between 1.60 and 1.68 eV.

Figure 7 shows the spectra from the area indicated by the dashed box in figure 6(c). The spectrum shows a number of peaks. What is striking is that the peaks in the region 1.59–1.66 eV (red line) seem to appear in the region 1.66–1.73 eV (blue line). It is highly likely that the blue emission peaks are the excited states of the red emission peaks. It is worth pointing out that though we do not observe excited states for all emission peaks along the QWT even if the ground states are observed in most of the QWTs of this thickness. It is only emission around 1.60 eV in all NWs that shows any significant excited state emission.

2.6. Hyperspectral imaging of a QWT on larger core diameter

As discussed above, the NWs with a hexagonal radial cross-section are mainly defined by 110 side facets, separated by small 112 facets. From previous reports \[30\], it is known that there is a difference in the thickness of the QWT on the different corner facets. The shape of the QWT is slightly chevron shaped, with three thicker 112A and three thinner 112B corners, as shown in figure 1(a). The facet widths of the QWT in the NWs presented above have dimensions smaller than the expected spatial resolution for individual facets in CL imaging. However, a few NWs in the samples have larger core diameters leading to wider facet sizes. This could be caused by growth from colloidal particles merging during the annealing before the growth, two closely spaced cores merging early during growth, or occasionally larger colloidal particles. The total diameter of these accidentally wider NWs is around 350 nm, as opposed to the 250 nm of the majority of the NWs. The 350 nm diameter levels we could potentially resolve the emission from the three facets facing the detection system when investigating the QWTs on thicker cores in the CL imaging. We do not expect to excite the facets facing down, so the majority of the emission originates from the three upward-facing facets. Figure 8(a) shows an average spectrum of one NW with a thicker core in the sample with a nominal 2.0 nm QWT thickness. There is a slight blueshift compared with the typical spectrum of the 2.0 nm QWT sample in figure 2(a). This is a direct effect of growing the QWT on a thicker diameter core and consequently covering a larger surface area, resulting in a thinner QWT thickness and a blue shift of the emission. Figure 8(b) shows a series of monochromatic images extracted from a hyperspectral data cube, as well as the panchromatic image showing the integrated emission from the same NW. The detection windows and steps are both 10 meV. Since all energies were recorded at the same time as a data cube, there is no drift between the monochromatic images and the spatial variations observed for each emission energy are
accurate. The lack of drift is confirmed by the SEM image that was recorded at the same time as the CL image. As demonstrated for the QWTs grown on the thinner cores, there are spectral variations along the length of the NW. A careful comparison of the lateral distribution of the emission shows that there is an asymmetry in the emission intensity across the nanowire diameter with detection energy. This is a clear indication that it is possible to observe emission resulting from the asymmetric QWT cross-section of a NW lying on a 110 facet. From the asymmetry of the QWT corners, as shown in figure 1(a), there could be a systematic difference in the emission energy from the two types of corners, where one corner should exhibit a lower energy that the other corner. However, we do not observe any clear variation between the three facets we observe the emission from. A typical example is the 1.83 eV emission. There are clear instances of emission hotspots on the left and right sides of the NW, as well as in the centre.

3. Discussion and conclusions

We have studied NWs containing single QWTs of three different thicknesses. With increasing nominal thickness, the emission energy is reduced from just below the bandgap of the AlGaAs towards the emission from bulk GaAs and thereby also the GaAs core. However, we do not observe any emission from the barrier, which indicates a fast carrier capture of the QWT and the GaAs core. Even for the thickest QWTs, there is still significant quantization and the QWT emission is clearly distinguishable from that of the core. The 6.0 nm thick QWT in this report has a low temperature emission centred around 1.62 eV. A previous publication [9] of QWTs in the same series reported emission centred at 1.58 eV from QWTs with an 8.0 nm thickness. This is thicker than the QWTs in the current report, but the emission is still significantly different from the core emission. When compared with theoretical calculations of the expected emission from a QWT, there is a spread in QWT thickness of ±30% for individual NWs, leading to a broadening of the emission from single NWs. The width of the emission peak ranges from 80 to 130 meV. As expected, the broadening increases when the QWT thickness is reduced from 6.0 to 2.0 nm. This is in line with a larger quantization with reduced thickness, where a similar spread in thickness leads to a larger spread in the quantization the thinner the QWT is. In contrast, the thinnest QWTs exhibit the least spread, 80 meV in the emission. According to the theoretical calculations, very thin areas of the QWT will not have any confined states, as the high energy side of the emission is in effect limited by the barrier. It is also quite likely that the QWT is not continuous along the NW with patches of nonexistent QWT.

The spread of thicknesses in the current single QWTs is probably too large to achieve higher gain for operation in single wavelength nanowire lasers. Similar structures have been used to obtain room temperature lasing [34]. The QWT structure in that case was a stack of eight radial QWTs, resulting in lasing with a line width of less than 2 meV at room temperature. Unlike the NWs used in this study, the diameter and length of the NWs in [34] were selected to achieve a Fabry-Pérot (FP) cavity along the NW length. The full width at half maximum of the integrated QWT emission from single NWs in the present study is about 50–60 meV, which means that only a fraction of the QWT would participate in single wavelength lasing. The way around this is to increase the number of QWTs in the single NWs, just like in [34]. It is worth pointing out that we do observe a few sharp peaks in the emission from the 2.0 nm QWT. This could potentially be interpreted as lasing and/or resulting from FP modes in the present NWs. However, we can rule out lasing as these sharp peaks do not increase significantly in intensity compared with other emission even when the probe current is increased by a factor of 50. With a higher probe current, the spectral width is not reduced, but in fact broadens slightly. These peaks are not likely to originate from FP modes either. We would expect these modes to be present for all emission along the whole length of the NW, as was observed for GaAsSb-based NW lasers in [6]. They are more likely to originate from local thickness variation, creating quantum dot like states, as discussed in reference [29].

As discussed earlier, we know that the QWs are not flat along the side facets, but slightly wedge shaped, with two thick QWs meeting at the three 112A corners and two thin QWs meeting at the other three 112B corners [30]. In the radial
cross-section, the QWT appears to consist of three chevrons. This could lead to localization of the states around the three thicker QW corners. As the NWs were grown from the nominally 50 nm gold seed particles, the resulting side facets are not wide enough to spatially resolve the adjacent QW corners by conventional CL work in an SEM. We would need the spatial resolution of CL in a TEM to distinguish between the different emission arising from the asymmetric thickness of the QWT [32]. However, the high acceleration voltage needed bleaches the emission before it is possible to record any useful CL data. After being studied by TEM, the emission from GaAs is usually gone. Even NWs that were not imaged tend to be optically dead after only being inside the TEM during investigation.

In the present samples, there are a few NWs that by accident have thicker cores, as discussed above. There is for instance one in figure 2. For these thicker NWs, we can observe a variation in the spatial origin of the emission across the NW. There appear to be at least three spatial origins of the emission, two side facets and the centre facet facing upwards. There is however no consistent trend that one side of the NWs generally has lower emission energies that the other. In order to be able to confirm this, we can outline an approach, using slightly wider cores, or cores plus a thicker lower barrier. Ideally, these NWs should be studied in side view standing on the substrate. That way, we can orient the NWs such that a corner is facing upward in the SEM, exposing only two facets, and we can control the type of corner (A or B), thin or thick. The supplementary information (available at stacks.iop.org/NANO/31/424001/mmedia) shows an accidentally thicker NW with a corner facing upward when transferred to a Si substrate. In this case, monochromatic images appear to show two lines of emission spots, consistent with the two facets facing upward. The supplementary information also shows an SEM and CL image of an intentionally much thicker NW in side view on a cleaved substrate. This particular NW was cleaved through the centre to reveal the interior of the axial cross-section of the QWT, similar to the base in figure 1(e). It is clear from this image that it is possible to access two sides of the QWT. In the part where the NW was not cleaved, the three facets are clearly resolved in the image. The QWT in this particular NW is too thick to show any significant quantum confinement, with only minor variations in the emission energy (not shown here). But it shows that it is possible to access thickness variations.

In conclusion, we have presented a study of a series of GaAs/AlGaAs QWTs with different thicknesses, using spatially and spectrally resolved CL at liquid He temperatures. We have used both single and multiple wavelength detection. All QWTs show a thickness spread of ±30% (or a factor of two) for single NWs. With the exception of the thinnest (1.5 nm) QWT, the QWTs appear to be continuous along the length, as revealed by images of the integrated QWT emission, in panchromatic imaging. In contrast, the thinnest QWT exhibit a patchy emission pattern, even in panchromatic images. This can be interpreted as an incomplete QWT coverage, or at least a QWT that is too thin to have any confined states. All QWTs show an apparently random scattering of emission peaks along the length, without any consistent gradient in the peak positions. This leads us to conclude that there is no gradient in the QWT thickness along the NWs. The main portion of the NWs have diameters where it is difficult to distinguish the spatial origin of the QWT emission in the radial direction. However, a few NWs have a larger diameter, where we are able to distinguish between three facets for NWs transferred onto Si substrates. Though we can resolve different spatial origin, we cannot reveal any trend in thickness between the three facets facing the detection system.

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