1.32-µm InAs/InGaAs/GaAs quantum-dot lasers operating at room temperature with low-threshold current density

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ABSTRACT

We report on the growth and characterization of low threshold 1.32-µm quantum dots (QDs) laser diodes. The quantum dot active region was optimised to get the highest photoluminescence emission and the lowest Full Width at Half Maximum (FWHM). From samples containing multilayer QDs and using the Limited-Area Photoluminescence (LAPL) technique we have shown that the gain of an N-layer structure is higher than N times that of a single layer. This enhancement is attributed to the increase of the quantum dot density in the upper layers and also to the use of the high growth temperature spacer layer . Broad area laser diodes were processed from the grown samples containing three layers of InAs QDs grown directly on GaAs and capped with 4-nm-thick $In_xGa_{1-x}As$ layer. Than measurements were performed at room temperature under pulsed excitation. The laser diodes operate at room temperature and emit between 1.29 and 1.32-µm which is beyond the strategic telecommunication wavelength. The characteristic temperature is around 80 K and very stable in the hole range of the operating temperature (from 0 to 90 °C). The internal quantum efficiency is 53 % and the modal gain per QD layer was estimated to be ~ 6 cm^{-1}. For an infinite cavity length a threshold current density of 8 A/cm^2 per QD layer was obtained. From the calculation of the optical confinement of QDs, we have estimated a material gain of 1979 cm^{-1}.

Keywords: Quantum dots, laser diode, room temperature, InAs/InGaAs, low threshold, Limited Area PL

1. INTRODUCTION

Semiconductor laser diodes having quantum dots in their active zone are expected to show high gain, ultra-low threshold current densities and temperature insensitive operation due to the δ-like density of states[1,2]. The realization of 1.3-µm edge-emitting lasers is one of the most challenging goals in the technology of GaAs-based devices due to matching with the transparency window of optical fibers. Recently, QD growth techniques using Molecular Beam Epitaxy (MBE) have progressed to enable impressive device characteristics at this strategic wavelength including RT continuous-wave operation lasers with low threshold current density, high characteristic temperature and high output power[3,4]. For the realization of such laser diodes, InAs/InGaAs system was shown to be the ideal system. One of the main problems of QD lasers is gain saturation. Therefore, the use of more than one layer of QDs is necessary. The optimization of growth parameters can ensure a very good control of size, shape and density of arrays[5]. Such optimisation is required to improve optical properties and to increase the gain by a factor of N when stacking N layers of QDs. This would allows the fabrication of devices with reasonable cavity length without using high reflection coatings and to avoid gain saturation at room and high operating temperatures. In this manuscript, we show that careful optimisation of the active region and the stacking of multilayer QDs results in a linear increase of the gain with the number of QD layers and devices operating at room temperature with low threshold current density.

2. OPTIMIZATION OF THE ACTIVE REGION

All samples were grown by MBE using a RIBER COMPACT 21-T system. Before growing a complete laser structure, an optimization of the active region is necessary. First uncapped samples were grown and analyzed by Atomic Force Microscopy (AFM). After oxide removal at high temperature (~620 °C), a 200-nm-thick GaAs buffer layer was deposited at a growth rate of 1 Ml/s, than the substrate temperature was lowered to <500 °C for the growth of the QDs.

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This low temperature is used to avoid In segregation and InAs evaporation during the growth[6]. Three important growth parameters, the growth temperature, the InAs growth rate and the amount of InAs, were varied separately in order to get a high density and a uniform size distribution. The In/As flux ratio was fixed to 20. The surface quality was controlled by RHEED pattern. The beginning of 2D-3D transition corresponds to a change of the RHEED pattern from streaky-like to spotty-like. After the deposition of 2.8 Mls of InAs, a growth interruption under As flux follows than the substrate temperature is lowered to 300 °C. The AFM analysis of the grown samples shows that the best results in term of size uniformity and a high density of QDs, is obtained with InAs growth rate of 0.04 Ml/s, growth temperature <500 °C, and InAs thickness of 2.8 Mls. A sheet density of the order of 1.14×10^{10}dot/cm^2 was obtained as shown in figure 1. Statistic analysis, performed by software, reveals a uniform distribution, with mean height of 6 ± 1 nm and average diameter of 45 nm.

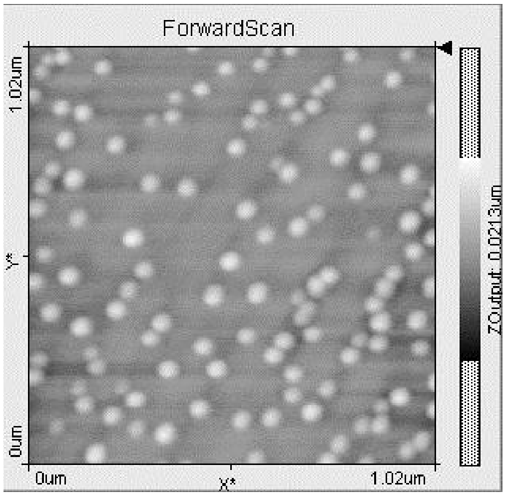

Figure 1: AFM image of one uncapped InAs QDs layer grown on GaAs with a growth rate of 0.04 Ml/s

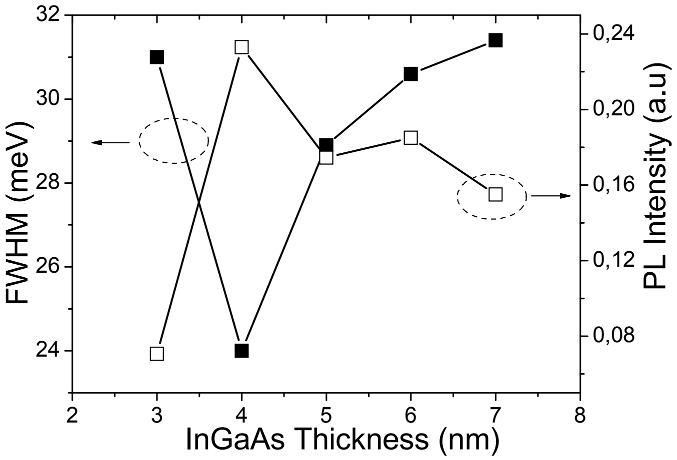

Figure 2: PL intensity and FWHM as a function of $In_{0.18}Ga_{0.82}As$ thickness

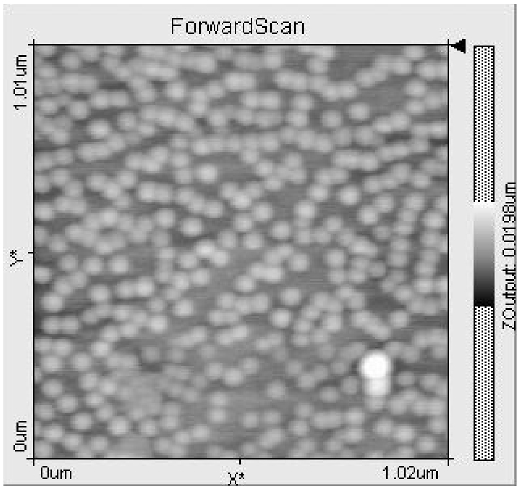

Figure 3. AFM image of the third uncapped InAs QDs layer

The insertion of these QDs in a GaAs barrier provides a photoluminescence emission wavelength from the ground state not longer than 1250 nm, with a FWHM of 24 meV at room temperature. A growth interruption of 90 s under the same As flux used for InAs QDs, between QDs and GaAs cap layer provide the optimum result in terms of narrow line width and high efficiency. To red-shift the emission wavelength beyond 1.3-µm, the strain layer reducing technique[7] was chosen and InAs QDs have been capped with few nm-thick layer of $In_xGa_{1-x}As$.

The optimum thickness of $In_xGa_{1-x}As$ layer was selected by analysing several samples containing 3, 4, 5, 6, 7 nm-thick InGaAs layers. An indium content of 18% was used to reach wavelength emissions beyond 1.3-µm. The pause time was kept constant.

Figure 2 shows the Full Width at Half Maximum (FWHM) and PL intensity as a function of $In_{0.18}Ga_{0.82}As$ thickness. A thickness of 4 nm gives the lowest FWHM of 24 meV and the highest PL signal. This thickness was used for the growth of the following samples.

One of the main problems of QDs lasers is gain saturation[8]. It's necessary to increase the optical gain in a QD laser structure by stacking several QD layers. In order to ensure a very good layer by layer reproducibility, the growth of the 40 nm GaAs barrier was performed as follows: After the InGaAs quantum well, a 5 nm of GaAs are grown at low temperature (the same as InAs QDs) to avoid InAs evaporation, afterwards, the temperature is increased to ~ 600°C for the growth of the remaining thickness. In addition to a better separation between the strain field induced by the buried QDs and the upper QDs, and to a better GaAs optical quality, the growth of the spacer layer under these conditions resulted in an enhancement of the QD sheet density, as the number of layer increases. As shown in figure 3, which is an AFM of the third stacked uncapped QD layer, the sheet density is found to reach 3.2×10^{10}dot/cm^2, preserving the high size uniformity of the first QD layer.

This can be explained by the combination of higher overall strain induced by InAs QDs and InGaAs quantum well and the high growth temperature of the GaAs barrier layer. This affects the surface morphology of GaAs barrier in terms of increased density of growth terraces (which represent further QD nucleation sites) on high surface quality, on which a higher density of QD could be grown without defect. To study the effect of the stacking on the optical properties of InAs/InGaAs QDs, Limited Area Photoluminescence (LAPL) were performed on three samples containing three, five and seven layers of QDs. This technique involves probing a microscopic area on the sample[9,10]. To reduce the probed area we coated a quartz wafer with a photolithographically defined Ti/Au layer containing an array of widely spaced holes of 200-µm which could be placed metal layer down on any sample. Than we pump throw one hole and we detect only emission from the probed area. The emission coming from carriers diffused away from the probed area will not be detected, allowing to reach ground state emission saturation. For optical pumping we used a mode-locked Ti:Sa laser with a 80 fs pulses and 82 MHz repetition rate. The excitation wavelength is 800 nm, thus mainly exciting the GaAs layers. Knowing the optical absorption of the GaAs at 800 nm which is $\sim 1.33\times10^4$ cm^{-1} [11], we estimate that the GaAs layers containing QDs, which have a total thickness of 500 nm, absorb ~ 48 % of the pump radiation. Using the usual PL technique measurement we can't compare the relative gain intensity because we didn't reach the ground state intensity saturation. The ground state photoluminescence emission of the three samples is centred at 1300 nm and as expected PL intensity increases with the number of QD layers. Figure 4 shows the LAPL emission from the sample containing 7 stacked layers of QDs, the ground state emission increases and saturates for an optical power excitation of 605 W/cm^2 while the intensity of the first and second excited state emissions continue increasing.

The inset of figure 4 shows the ground state LAPL intensity as a function of power excitation, as observed the intensity increases than saturates and it starts to decrease for a high power optical excitation probably due to thermal escape of carriers from the ground state.

The ground state saturated intensity is proportional to $2N/\tau$, where the factor of 2 accounts for the degeneracy, N is the number of dots contributing to the signal and τ is the radiative lifetime[9]. It is possible to compare the relative ground state saturated gain since it's proportional to N.

Figure 5 shows the LAPL emissions for the samples containing three, five and seven layers corresponding to the ground state emission saturation. As expected the GS saturation intensity increases with increasing the number of layers. In addition the normalized GS saturation intensity relative to a single layer increases with increasing the number of stacked layers confirming the AFM observation. This effect is different to the one observed in ref [12] in which the QDs density decreases when increasing the stacking layer number. In addition the FWHM increases slightly for the three samples from 24 meV to 28 meV in comparison with the active region containing one layer of QD which indicates that only a small dot size dispersion is introduced by the stacking procedure.

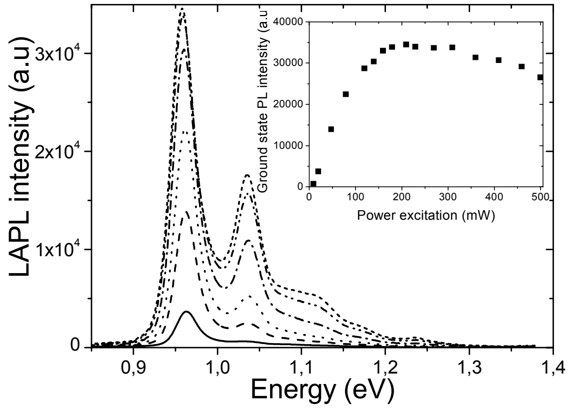

Figure 4. Room temperature Limited Area PL emission spectra of a sample containing seven QD stacked layers under different pulsed optical excitation. The inset shows the ground state LAPL intensity as a function of power excitation

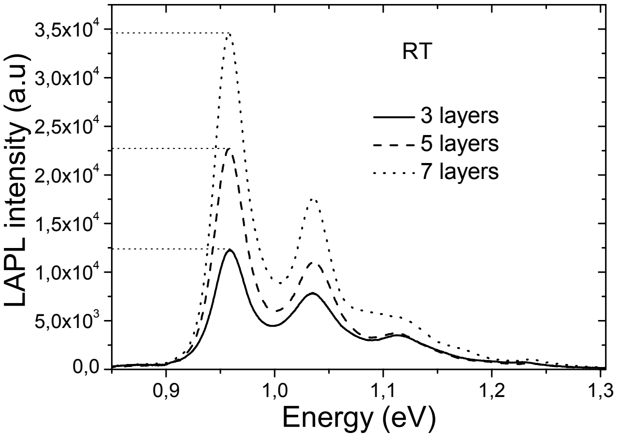

Figure 5. Room temperature Limited Area PL emission spectra of three samples containing three, five and seven QD stacked layers under different pulsed optical excitation corresponding to the GS intensity saturation

This is very important for QD laser active medium[13,14], because the optical gain increases linearly without any degradation of the optical properties. In addition the use of the high growth temperature spacer layer reduces the non radiative centers by the suppression of defects formation.

3. GROWTH AND PROCESS OF THE COMPLETE STRUCTURES

We have grown two structures having the same design, we changed only the indium content in the $In_xGa_{1-x}As$ quantum well. The growth of the complete structures was performed on (100) n-type GaAs substrate. After oxide removal at high temperature, the layers were grown in the following order: a 200 nm-thick n-type GaAs buffer layer, a 1.5-µm-thick $Al_{0.7}Ga_{0.3}As$ n-type (5×10^{17} cm^{-3}, Si) cladding layer, an undoped active region consisting of three stacked $InAs/In_xGa_{1-x}As$ QD layers separated by 40 nm-thick GaAs barriers and enclosed between GaAs spacer layers. The total thickness of the active region is 500 nm. A 1.5 µm-thick p-type $Al_{0.7}Ga_{0.3}As$ (5×10^{18} cm^{-3}, Be) cladding layer, and finally a 0.3-µm p^+-GaAs cap layer. The active region was grown using the optimized growth parameters as demonstrated previously. A growth rate of 1 µm/h and a growth temperature of 600 °C were used for the growth of GaAs waveguide and $Al_{0.7}Ga_{0.3}As$ cladding layers. N-type and p-type $Al_{0.7}Ga_{0.3}As$/GaAs digital grading alloys were grown at the interfaces between GaAs and $Al_{0.7}Ga_{0.3}As$ to enhance carrier transport and reduce the series resistance of the structure[15]. The wafer was processed to get broad area devices. Stripes of 100 µm-width were realised by chemically etching 1.8 µm (GaAs cap layer and cladding layer). A thermal evaporator was used for the deposition of metallic contacts. P-type contact consists of a Pd/Zn/Pd/Au (15 nm/3 nm/ 30 nm/200 nm) multilayer. As n-type contact, GeAu/Ni/Au (70 nm/30 nm/250 nm) was deposited on the back of the structure. Diodes of different cavity lengths (L ≥ 0.75 mm), with uncoated as–cleaved facets were studied. The diodes were mounted on a copper holder heat sink, to dissipate thermal heating, and micro-bonded. Electroluminescence measurements were performed in pulsed regime, with a duty cycle of 1% and a pulse width of 1 µs, and the spectra were collected by an optical spectrum analyser.

4. OPTICAL AND ELECTRICAL CHARACTERIZATION

Figure 6 shows the emission spectra at room temperature in pulsed regime (1% duty cycle and 1 µs pulse width) of two laser diodes having 14% and 18% as indium content in the $In_xGa_{1-x}As$ quantum well. The wavelength emission can be tuned from 1.29 to 1.32 µm. The cavity length and the stripe width were 4 mm and 100 µm respectively. The emission spectra are multimode which is a typical behaviour of broad area lasers.

In the figure 7, we have plotted the output power emitted as a function of current. The measurement was performed at room temperature and in pulsed regime. The threshold current density is 43 A/cm^2 which is equivalent to ~14 A/cm^2 per quantum dot layer. The inset of figure 7 shows emission spectra of the device below and after threshold.

To determine the internal losses and the internal quantum efficiency, we have plotted the reciprocal differential quantum efficiency as a function of cavity length and we fitted the data by the well known formula:

$$\frac{1}{\eta_d} = \frac{1}{\eta_i} \times \frac{\alpha_i + \alpha_m}{\alpha_m} \qquad (1)$$

where, η_d is the differential quantum efficiency
η_i is the internal quantum efficiency
α_i the internal loss (cm^{-1})
α_m the mirror loss (cm^{-1})

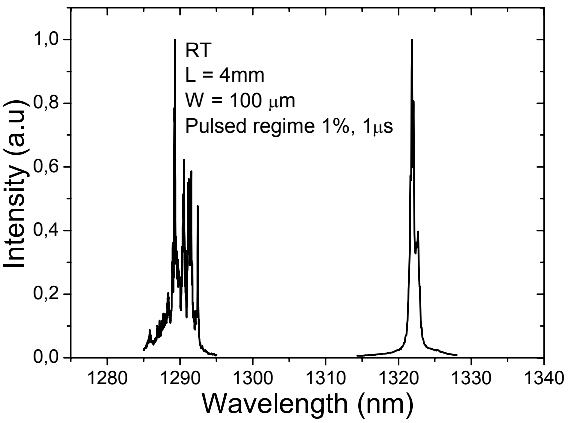

Figure 6: Emission spectra of tow different devices containing three layers of InAs/InGaAs QDs with two different composition of indium. The measurements were performed at room temperature and in pulsed regime

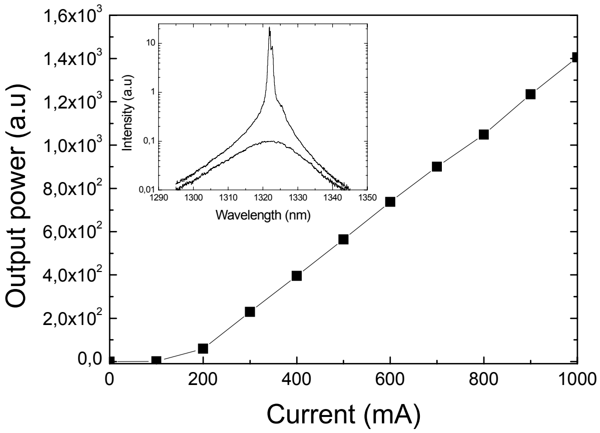

Figure 7. Output power emitted versus current at room temperature and in pulsed regime from 2-mm-cavity length. The inset shows emission spectrum below and after threshold

From figure 8 an internal loss coefficient as low as 1.5 cm^{-1} and an internal quantum efficiency of 53 % were extracted. The value of internal loss is comparable to the one obtained in ref [15]. The value of internal quantum efficiency can be increased by increasing the number of QD layers and also by using graded index separate confinement heterostructure which provides better efficiency of carrier injection to the active region[15].

In figure 9 we have plotted the threshold current density as a function of reciprocal cavity length at room temperature and in pulsed regime to avoid device heating. For an infinite cavity length the threshold current density decreases to 25 A/cm^2 which corresponds to ~ 8 A/cm^2 per QD layer. This value is among the best reported values for QD lasers operating near 1.3-µm. From the temperature dependence of threshold current density, a characteristic temperature T_0 of 78 K was measured in the temperature range 0°C-90°C. These results were obtained without specific optimization of the complete structure such as doping profile or the use of high reflection coatings on both facets, which are expected to improve the characteristic temperature[16] and threshold current density respectively.

The shortest cavity length for which the ground state lasing was observed was 750-µm for the QD laser structure containing three layers of QDs. Knowing the internal loss (1.5 cm^{-1}) and calculating the mirror loss following the well known formula:

$$\alpha_m = \frac{1}{2L} Ln\left(\frac{1}{R_1 R_2}\right) \qquad (2)$$

where, L is the cavity length

R_1 and R_2 are the reflectivity of the front and rear facets

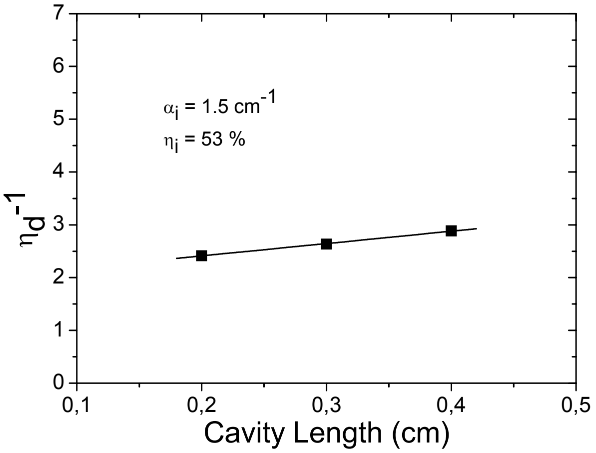

Figure 8: Reciprocal differential quantum efficiency as a function of cavity length at room temperature

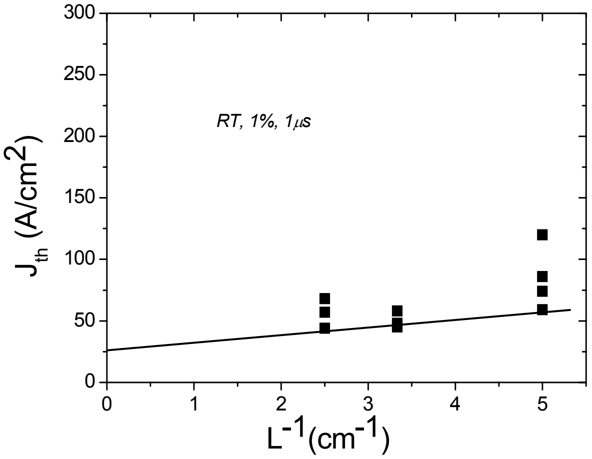

Figure 9. Threshold current density as a function of cavity length for three stacked layers of InAs/InGaAs quantum dot lasers at room temperature and in pulsed regime

and using the threshold condition which is:

$$g_m = \alpha_m + \alpha_i \qquad (3)$$

where, g_m is the modal gain

α_i is the internal loss

α_m is the mirror loss

we deduced a maximum modal gain of 17.5 cm^{-1} which corresponds to ~ 6 cm^{-1} per quantum dot layer. This value is among the highest values reported in the literature.

In order to estimate the material optical gain, it is necessary to estimate the optical confinement factor Γ of the QD layers. The effective interaction volume of the QD exciton with the photon field assuming ellipsoidal like dots with a base diameter of 45 nm and a height of 6 nm is similar to a cylinder with the same diameter and a height of 4 nm. The confinement factor calculated for a three quantum well laser structure with an active layer thickness of 4 nm and having the same waveguide is estimated to be $\Gamma_{QW} = 0.292$ %. To obtain the confinement factor of our three QDs layers, we have multiplied Γ_{QW} by the dot coverage ~31% of these three layers resulting in a confinement factor of $\Gamma_{QD} = 0.0088$. From the modal gain of 17.5 cm^{-1} and using the following formula:

$$g_{\mathrm{mod}} = \Gamma_{QD} \times g_{mat} \qquad (4)$$

we estimate a material gain of 1979 cm^{-1}.

5. CONCLUSION

We have grown by MBE active regions based on InAs/InGaAs system. After the optimisation of the growth parameters, complete structures containing three layers of QDs were grown, processed and characterized. From LAPL measurement on three samples containing three, five and seven stacked layers, we have demonstrated an enhancement of the gain per QD layer with increasing the number of QD layers. The processed broad area lasers operate at room temperature and the maximum wavelength achieved is 1.32 µm. The internal loss was as low as1.5 cm^{-1} and for an infinite cavity length a threshold current density as low as ~ 8 A/cm^2 per QD layer was measured. A characteristic temperature T_0 of 78 K was measured in the temperature range 0°C-90°C. From the maximum achievable modal gain we have estimate by calculating the optical confinement factor a material gain of 1979 cm^{-1}.

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