We demonstrate how to build a vibrating wire resonator for phonon excitation in liquid helium. The resonator is designed as a nanoscopic mechanically flexible beam machined out of a semiconductor/metal-hybrid. Quenching of the mechanical resonance around 100 MHz by phonon excitation in liquid $^4\text{He}$ at 4.2 K is shown. First measurements operating the nano-resonator in a dilution of $^3\text{He}/^4\text{He}$ at 30 mK are presented.

Vibrating wire resonators (VWR) are standard bolometers for the quantum fluids $^3\text{He}/^4\text{He}$ [1]. The general idea is to immerse a metallic wire into superfluid helium and to induce a mechanical vibration by applying a magnetic field while simultaneously sending an alternating current through the wire. Usually these wires are resonating at several kHz with deflections on the order of some microns. The wire moving in the superfluid will generate a phonon flux, which is directed parallel to the plane of motion of the wire. With these macroscopic wires excitations in $^4\text{He}$ are usually not found, since the Landau critical velocity is not in the accessible range.

Here we present a new approach to build such phonon radiators for applications in spectroscopy of quantum liquids. In contrast to previous resonators operating in the kHz-range only, we focus on the realization of wires or more specifically on suspended hybrid Si/metal-beams with nanometer dimensions and hence resonance frequencies up to 1 GHz [2,3]. We will first discuss processing of the nanostructures and then proceed to the experimental setup. Moreover, we show measurements allowing us to calibrate the attenuation of the nano-VWR in liquid $^4\text{He}$. Finally, we show first results on resonating nano-VWRs in $^3\text{He}/^4\text{He}$ at 30 mK.

The beams are machined from commercially available Silicon-on-Insulator (SOI) wafers with a top layer thickness of 205 nm and a sacrificial layer of 400 nm. Optical lithography and evaporation of 180 nm NiCr-Au/Ti are used to define the necessary bond pads and an etch mask (Ti), which is then removed in the wet etch step. An electron beam writer (JEOL 6400) is used to define the nanomechanical resonator, consisting finally of the metallic line on top (Au) and the Si supporting membrane. In the following step the sample is etched in a reactive ion etcher (RIE) using CF$_4$ as an etchant. The section of the sample, which is not covered by metal, is milled down by 200 nm. Finally the sacrificial layer is removed using diluted (2%) hydro-fluoric acid (HF) at an etch-rate of 10 nm/sec.

In the right inset of Fig. 1 the suspended beam is shown in a scanning electron beam micrograph: The beam is freely suspended between two tuning gates, coupling capacitively. The beam has a length of 1 $\mu$m, a width of 200 nm, and the gates are covered by a 50 nm Au layer. The gates can be applied to tune the mechanical
resonance by biasing up to about 10 V. For the measurements we employ a Hewlett-Packard network analyzer (HP 8751A), monitoring amplitude and phase of the resonator simultaneously with Hz-resolution. The beam’s resonance is excited by the alternating current at radio frequencies and the static magnetic field applied in plane. At resonance a magnetomotive force is induced, which in turn can be read out. In our case, the reflection of the signal is determined, which is transduced upon the beam. For sensitive detection of the induced voltage signal a double sided high-gain (15 dB) amplifier is brought into the line feeding the circuit. The amplifier is optimized for a frequency response between 1 and 500 MHz. The resistance of the cables and the leads in the sample holder is 50 Ω, the dc-resistance of the sample is found to be 30 Ω, thus a fairly good impedance matching is guaranteed.

First we measured resonance curves characterizing the elastic properties of the beam in linear (L) and nonlinear (NL) response; these measurements are shown in Fig. 1. The resonance frequency is around 96 MHz at 4.2 K and shifts to lower values when the resonator enters the nonlinear regime. The reflection factor is defined by

$$ r = \frac{P_{in}}{P_{out}}, $$

obviously it decreases with increasing power. The resonator can be modelled as a typical Duffing oscillator using:

$$ y''(t) + \gamma y'(t) + \omega_0^2 y(t) + k_3 y^3(t) = A \sin(\omega t), \quad (1) $$

where $y$ is the elongation, $\omega_0 = 2\pi f_0$ the eigenfrequency of the beam, $\gamma = \omega_0/Q = 4.5 \times 10^5 \text{ s}^{-1}$ represents the damping constant and the driving amplitude is given by $A = 1.4 \times 10^5 \text{ m/s}^2$ at $-63 \text{ dBm}$ and $2.8 \times 10^6 \text{ m/s}^2$ at $-37 \text{ dBm}$. The shift to lower frequencies implies that for the cubic constant in the Duffing equation we have $k_3 < 0$. Attenuation commonly shifts the eigenfrequency of a linear resonator to lower frequencies and deteriorates the quality factor. In the measured resonator a quality factor of 2000 was observed. In a nonlinear resonator the eigenfrequency changes in addition with increasing attenuation, since the amplitude is reduced and the resonator is driven closer to the linear regime. In our measurement this shift leads to higher frequencies. Thus, if the resonator is damped by liquid helium, a shift in the oscillating frequency first to higher and then to lower frequencies and a broadening of the resonance is expected.

Fig. 2(a) shows the measurement of the reflected power during filling of the sample holder with 4He when the wire is driven in linear (L) response. The sample holder was cooled to 4.2 K. The attenuation by the gas leads to a decrease of the resonance amplitude, a frequency shift to lower frequencies and a broadening of the resonance. When liquefaction of the 4He starts (shown in the last trace), the resonance disappears completely. As seen in this figure we find even in the linear regime of the resonator’s response a dispersion when the 4He content is increased. This corresponds to an effective momentum transfer to the 4He-atoms impinging onto the resonator. We estimate this momentum transfer per atom to be $1.9 \times 10^{-44} \text{ Ns}$ at $p \approx 20 \text{ mbar}$, $T = 4.2 \text{ K}$, and at an excitation power of the network analyzer of $-68 \text{ dBm}$.

The plane of phonon emission can be chosen according to the direction of the magnetic field, as sketched in the inset of Fig. 2(a). In the present case the magnetic field was applied perpendicular to the plane of the sample, hence excitations are propagating in-plane away from the beam. Obviously the electrodes in the current setup disturb the free propagation of phonons. This might cause a back-flow and hence turbulences in the heat flow. Repeating the measurement in the nonlinear (NL) regime enables us to observe the motion of the beam even in the liquid phase. This measurement is depicted in Fig. 2(b): The first lower six curves are taken in 4He gas while the upper four curves are taken in the liquid phase. As seen the traces are changing drastically in the gaseous phase at some 10 mbar, since with raising pressure the attenuation of the beam’s motion is increased due to the enhanced scattering of 4He-atoms. On the other hand damping in the liquid depends only on the viscosity, which does not change when supplying more helium. Thus the curves change only slightly when the beam is immersed in the liquid phase. Hence, we can conclude that it is possible to create excitations in liquid 4He.

The main focus naturally is the possibility to apply the nanomechanical resonators as phonon generators in superfluid helium. This is especially interesting, since the motion of the beam is fast compared to the critical velocity in 4He. Until the beam reaches the velocity, which is required to create vortex states no attenuation should be present, since the fluid is not excited by the motion of the beam. Further acceleration leads to the excitation of vortex states in the fluid resulting in an increased energy consumption. This can be seen in a flattening of the resonance curves. In 3He the critical velocity is given by the energy required to break the superfluid state, which is in the mm/s range. In 4He it is given by the creation of vortex states at low pressures and the excitation of rotons at higher pressures. The corresponding velocities are about 25 m/s. With cold neutron scattering experiments even the zero pressure critical velocity has been measured ($v_c = 60 \text{ m/s}$). Therefore vibrating wire experiments have only been successful in 3He, while in 4He the critical velocity has been reached with accelerated charged ions.

In order to verify that we are able to reach the critical velocities, we monitored the velocities of the beam depending on the input power and the amount of 4He in the sample holder. We did this by calculating the maximum amplitude $Y_{0,max}$ during one cycle of the oscillation using the equation:

$$ Y_{0,max} = \frac{A}{\sqrt{1 + k_3 A^2}}, $$

where $A$ is the driving amplitude and $k_3$ is the cubic constant.
\[ Y_{0,\text{max}} = \frac{|BI_0|}{2m_{\text{eff}}\omega_0 \mu} \]  

Here, \( \mu = 2.23 \times 10^5 \text{ s}^{-1} \) is the damping coefficient of the mechanical system, \( l = 2L/\pi = 1.165 \mu\text{m} \) and \( m_{\text{eff}} = 3.418 \times 10^{-16} \text{ kg} \) are the effective length and effective mass of the resonator, \( B \) the magnetic field. The amplitude of the input current at \(-63 \text{ dBm}\) is \( I_0 = 4.09 \times 10^{-6} \text{ A} \) and at \(-37 \text{ dBm}\) it is \( 8.16 \times 10^{-5} \text{ A} \). Subsequently we obtain \( Y_{0,\text{max}} = 9.79 \text{ nm} \). The parameters of the Duffing eq. (2) can be extracted from the measurements in the nonlinear regime. The velocity is then estimated via

\[ v \propto fY_{0,\text{max}} \]

In the linear regime we find a linear dependence on the input power as long as no \(^4\text{He}\) is added. The maximum velocity in this case is \( 20 \text{ m/s} \). When filling with \(^4\text{He}\), this velocity is decreased until it finally reaches zero in the case of liquid helium (see Fig. 2). In the nonlinear regime we begin at a velocity of \( 20 \text{ m/s} \), which is then reduced to \( 5 \text{ m/s} \) in the liquid. The decrease of the velocity is mainly due to the deterioration of the quality factor. To reach the critical velocities in \(^3\text{He}\) we have to increase the velocity by a factor of 5, but this should be sufficient to observe excitations of the superfluid \(^3\text{He}\).

For the observation of such excitations the sample is mounted in the mixing chamber of a dilution refrigerator. The suspended beam is immersed in a dilution of 6% \(^3\text{He}\) in superfluid \(^4\text{He}\) and cooled to 30 mK. The resulting measurements are depicted in Fig. 3: As seen the shapes of the resonances strongly varies from the original one determined at 4.2 K. Each resonance amplitude is monitored at different magnetic field values, hence avoiding spurious effects of the sample holder. We assume that the peculiar resonance shape is caused by the increased attenuation in the superfluid mixture. This seems to be counterintuitive, since conventional tuning fork resonators (TFRs) show less attenuation in superfluid phase of \(^4\text{He}\). These macroscopic resonators are operated at some 10 kHz with typical dimensions in the mm-range, compared to 100 MHz in our case. Moreover, a similar strong attenuation is observed when surface acoustic wave transducers are immersed into superfluid \(^4\text{He}\) at 1 K, where the attenuation is enhanced strongly \(^4\text{He}\), although the opposite behavior is expected. Hence, we can conclude that this strong attenuation is caused by the excitation of phonons and even rotons in the superfluid \(^4\text{He}\) (here we assume the \(^3\text{He}\) content to be negligible). An additional boundary resistance like the Kapitza resistance \( R_K \sim 1/T^4 \) \(^4\text{He}\) might be ruled out, since it should be observed for the TFRs as well.

In the measurements shown in Fig. 3 the resonance frequency drops continuously from 95.8 MHz (a), to 93.6 MHz (b), and to 72.2 MHz (c). This we attribute to the gradual disintegration of the Si supporting structure, while the metal on top remains flexible until it is melted.

Since the Si beam is stiffer than the top metal a gradual decrease of the resonance frequency is expected, when the Si beam is collapsing. A certain drawback of this resonator is the non-superconducting metal on top of the beam. A crude estimation of the Joule heating dissipated by the wire yields an energy of \( \sim 1.10 \times 10^{-20} \text{ J} \) per cycle, while the energy for excitations in superfluid \(^4\text{He}\) is on the order of \( 3.04 \times 10^{-23} \text{ J} \). Hence, we observe mostly black body radiation and not ballistic phonon emission. This problem can be overcome by using a superconducting metal on top of the suspended beam. However, from the data we obtained so far we can conclude that it is possible to create excitations in liquid as well as superfluid \(^3\text{He}\). Although, the phonon emission is not directed but isotropic, we are confident that a superconducting wire vibrating without dissipating the electromagnetic fields will create directed acoustical phonons propagating in superfluid \(^4\text{He}\). Furthermore, since a frequency range of 1 GHz seems to be a realistic goal with current lithography, velocities up to ten times larger than what we achieved are possible to reach. Thus even the regime of roton excitations might be accessible. Another experiment now in reach is the determination of the dispersion relation of phonons in \(^4\text{He}\). For the low energetic excitations the dispersion is purely acoustical up to frequencies of some 100 GHz. It is therefore possible to determine the dispersion of these excitations in the low energy limit ranging from some MHz up to possibly 1 GHz. Moreover, the eigenfrequency of the nanoresonators can easily be varied by a tuning gate.

In summary we presented measurements on nanomechanical resonators in gaseous and liquid \(^4\text{He}\) and in \(^3\text{He}/^4\text{He}\) at 30 mK. These measurements demonstrate strong attenuation of the mechanical excitations of the resonator. Since the elongation can be tuned even in the liquid, the resonators can be applied as nano-VWR in order to create vortex state and roton excitations in superfluid \(^4\text{He}\) and \(^3\text{He}\). In recent experiments quantum effects in superfluid \(^3\text{He}\) have been observed \(^{11}\). In order to observe quantum effects the objects moving in the liquid have to be smaller than the superfluid healing length. This length, which determines the width of the vortex states as well \(^{12,13}\), is about 50 nm in superfluid \(^3\text{He}\). Silicon beams with a width of 80 nm have already been fabricated \(^{14}\). Thus quantum effects in \(^3\text{He}\) are in the accessible range for those nano-VWRs. Our calculations show that the velocities required for these excitations are well in the experimentally accessible range. Although, a clear signature of directed phonon or roton excitation was not yet found, we presume that by replacing the non-superconducting metal on top of the electromechanical resonator by a superconducting one, we will obtain new insight into the excitation mechanisms of quantum fluids on a nanoscopic scale.

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Fig. 1: Fundamental resonance of the Si/Au-beam: Shown is the reflection coefficient of the beam from the linear (L) into the nonlinear (NL) regime at 4.2 K and 20 mbar He-gas pressure. Left inset: Circuit diagram of the experimental setup. The reflected signal is amplified and detected by the network analyzer. Inset on the lower right: Scanning electron beam micrograph of the vibrating wire resonator. The suspended beam consists out of a silicon supporting structure and a metallized top layer. The gates close by can be applied for electrostatically tuning the beam’s mechanical resonance.

Fig. 2: (a) Attenuation of the mechanical resonance amplitude by increasing $^4$He pressure as indicated until liquefaction in the linear (L) regime (−63 dBm input power, $T = 4.2\text{ K}$). The maximum velocity of the beam $v_{\text{max}}$ has been calculated for each curve and is given on the left hand side. In the inset a scheme for directed phonon generation is sketched. The magnetic field is oriented perpendicular to the high frequency current $I$. (b) Resonance curves of the beam in the nonlinear (NL) regime at different $^4$He fillings (4.2 K). Again the maximum velocity of the beam has been calculated. The motion is not suppressed completely in liquid $^4$He, thus allowing vibrational excitations.

Fig. 3: Resonator oscillating in a dilution of $^3$He/$^4$He at 30 mK. The different traces (a,b,c) are taken with the same device by increasing the magnetic field each time. The continuous decrease of the eigenfrequencies from (a) to (b) and (c) is caused by the disintegration of the Si supporting structure of the suspended beam (for details see text).
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