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論文内容要約

The interaction of modulated light with a material may result in a number of physical processes such as the thermoelastic waves, temperature gradients, surface distortions, thermal lensing in the surrounding medium and the emission of thermal radiation. The significance of this phenomenon can be realized from the fact that nearly all of these consequences have enabled interesting applications in material analysis, optical calorimetry, photothermal deflectometry, displacement spectroscopy and radiometry. Photoacoustics is generally referred to the first effect i.e. the generation of thermoelastic or acoustic waves that originate from the rapid and periodic modulation of temperature in the illuminated sample. Numerous studies have demonstrated the promising potential of photoacoustic techniques as a label-free noninvasive study tool across various clinical fields, from probing the general anatomy and molecular processes in biological systems to the monitoring of important biomarkers such as blood oxygenation, hemoglobin and glucose. The key requirements in PA detection of any particular analyte under investigation, irrespective of the nature of background medium, are the high detection sensitivity, analyte-specific selectivity and immunity to environmental fluctuations. Not to mention, with the focus being shifted towards more patient-centric healthcare models, size, user-safety and cost are additional important factors in clinical applications.

To date, piezoelectric elements or gas-phase microphones have been the primary transducers in the majority of photoacoustic studies. Piezoceramics provide markedly high central frequencies and large operating bandwidths in ultrasonic spectrum compared to gaseous microphones. These characteristics are particularly important for applications like photoacoustic tomography (PAT), as both the axial and lateral resolutions in the probed biological structure increase proportionally. By stark contrast, the substantially lower sensitivity (e.g. ~3×10^{-5} V/Pa for PZT elements) and SNR's (typical noise floors 90 ~100 dBA) than available with most commercial microphones (e.g. ~0.05 V/Pa with the lower limit of dynamic range ~14.6 dBA for B&K 4189) are serious barriers to their acceptance in applications other than the imaging modalities. Additional complications arise from the inherent affinity of the piezoceramics to thermal pickups from scattered light, the requirement of an external coupling media to compensate for their large acoustic impedance and the adequate suppression of the reverberating stress signals commonly referred to as mechanical ringing effect.

The use of a gas-microphone on the other hand, is either limited to samples with very high optical absorptions of the incident

wavelengths such as in trace gas studies or otherwise, resonance mode of an external acoustic cell is employed for sensitivity gains. In pursuit of improved detection sensitivities, a large number of efforts has been devoted towards optimum designs of PA cells to reduce the acoustic losses and also to minimize the effects of environmental interferences. While the cell resonators are widely applied in trace gas studies, relatively a small subset of efforts has been directed towards applications concerning the condense mediums. The progress in this dimension has largely been restricted due to the difficulties in achieving sufficient degree of sensitivity and steady operation with PA cells. Whether the sample being studied is gas, liquid or solid, beyond the fundamental design challenges, the principle restraints to the practical applications are essentially similar. The signal stability is the single most critical issue, as the resonant operation is affected by any change in the pressure, temperature and humidity/composition of the gas inside the cell. Interestingly the performance of QTF transducers too, both f_0 and Q, subject to same consequences. The temperature-related fluctuations, however, usually play the dominant role in either case. For instance, theoretical studies for the former show a net T^{1} dependence of PA signal on the temperature, while in actual measurements a much more profound impact $T^{-1.7\sim-2}$ has been reported. This is easy to comprehend from the strong affiliation of the acoustic speed with the thermodynamic properties of the gas, $c = \sqrt{kRT}$. Here $k = C_p/C_v$ is the specific heat ratio, R the gas constant and T the thermodynamic temperature. Any variation of gas temperature is directly reflected as the drifts of the cell resonance and the Q-factor. Even a slight temperature fluctuation might drive the measurements off the cell resonance, leading to inaccurate estimates of the signal amplitudes. This enormous vulnerability to temperature further discourages the use of very high Q resonators which are more liable to temperature fluctuations. Any potential solution to these challenges must provide ease of design and fabrication, high Q-factor performance, as well as a stable operation against any external instabilities.

Devices based on nano/microelectromechanical systems are capable of levels of performance that greatly surpass those of larger sensing systems. The unprecedented sensitivity in the detection of displacement, mass and force etc., has been achieved through the advances both in the microfabrication techniques that can mass produce devices with single-digit-nanometer precision as well as by the ingenious exploitation of these microsystems with various physical phenomenon. Here, we employ a microscale vacuum-packaged Si resonator with an off-chip optical readout to transduce PA elastic waves. This method offers a remarkably high Q-factor detection of miniscule PA signals while maintaining a steady and stable performance for prolonged measurements. The complete isolation of the micromechanical resonator from the ambient air effectively minimizes the influence of environmentally induced fluctuations. The employed coupling layout also benefits from the efficient solid-to-solid phase acoustic transmittance to the packaged resonator, in contrast to weak solid-to-gas coupling of the microphone diaphragm in the conventional setup. We demonstrate the potential of this method by correlating the vibration amplitudes of the micromechanical resonator with the intensity of PA signals from minuscule concentrations of the analyte. This novel scheme brings immense simplification to the measurement system by completely eliminating the need of additional transducer as the micro-resonator itself provides a transduction means for the PA elastic waves. Moreover, the combination of high Q-factor microscale resonator and the direct solid–solid interface approach also enable the use of compact laser diode sources, paving the way towards miniaturized sensing systems for PA techniques.

Chapter 2 presented the pertinent knowledge base for MEMS resonators and laid both theoretical and experimental foundations for the projects of the following chapters. After introducing some key concepts and basic characteristics of MEMS resonators, design guidelines for operating frequencies and optimization of the dissipation processes were discussed. Next, the details on the wafer-level processing steps used in the fabrication of devices were described . Then, the focus is laid on the basic theoretical formulations of photoacoustic and the integration micromechanical resonant device in the single wavelength photoacoustic measurement system was presented. Finally the experimental findings and discussions on the linear dependence of device signal on analyte concentration, incident optical power and output response stability were reported.

Chapter 3 described the practical application of the resonant sensor for photoacoustic biosensing. The vacuum-packaged microsensor attains Q ≈11,750 at fundamental mechanical resonance, a ~140-fold increase in the Q-factor compared to operation in viscous ambient environment, and a thermomechanical-noise-limited detection limit ~ 100 $pmHz^{-1/2}$. The device is adequately interfaced on a sensing platform with the excited specimen, harnessing the primary PA waves. This direct coupling strategy greatly overcomes the acoustic transmission losses inevitable to conventional PA cell systems dealing primarily with the perturbations in the resonant gas cavity. Steady operation of this functional approach is demonstrated by detecting minuscule PA signals resulting from physiological range variations of the trace amounts of glucose, embedded in gelatin-based synthetic tissues. The packaged device along with an off-chip optical readout successfully resolved the PA intensity changes at two distinct excitation wavelengths of 1552 nm and 906 nm. These results demonstrated the potential of the presented novel approach to broad photoacoustic applications spanning from non-invasive micro-biosensing modules to the analysis of solid and liquid analytes of interest in condense mediums.

Chapter 4 described the strategies to collect and focus the entire spectrum of the elastic waves propagating in the medium on to the resonant element employing the characteristic geometric designs for the resonant devices. It is noteworthy that the elastic waves transmit equally in all directions from the source point given that the medium is uniform in composition and exhibit isotropic properties. This implies that only a limited part of the pressure waves traveling towards the micromechanical, coupled on the interface platform, is received and amplified by the mechanical resonance. The remaining portion is lost in attenuation by repeated irregular reflections at the outer boundaries of the medium. Chapter reported on the theoretical and simulations models, and application of characteristic geometry based devices to this effect.

In summary the work of this thesis has presented a successful demonstration of the merging the MEMS and the photoacoustic technologies.