



Smartphones for sensing

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Abstract Simple, portable analytical devices are entering our daily lives for personal care, clinical analysis, allergen detection in food, and environmental monitoring. Smartphones, as the most popular state-of-art mobile device, have remarkable potential for sensing applications. A growing set of physical-chemical sensors have been embedded; these include accelerometers, microphones, cameras, gyroscopes, and GPS units to access and perform data analysis. In this review, we discuss recent work focusing on smartphone sensing including representative electromagnetic, audio frequency, optical, and electrochemical sensors. The development of these capabilities will lead to more compact, lightweight, cost-effective, flexible, and durable devices in terms of their performances.

Keywords Chemical sensing · Mobile phone · Devices · Analytical chemistry

1 Introduction

As a core communication device, the mobile phone is becoming increasingly popular in our daily lives. In 2014, the number of Chinese mobile phone users was 1.286

billion (94.5 % of the Chinese population) [1]. A wide variety of functional units and friendly operating systems make mobile phones eminently suitable for smart technological applications, and mobile phones have also attracted the interest of scientists. In comparison with traditional, larger instruments, smartphones exhibit the following advantages: (1) They can directly measure different physical quantities using various integrated sensors; (2) they enable communication with other devices through wireless interfaces; and (3) they are easy to operate without the need for professional training.

Recently, sensing applications at multiple scales, such as personal, group, and community sensing, have been developed [1]. Among these, sensing applications on mobile phones can be classified as participatory sensing and opportunistic sensing [2]. Sensing software is increasingly being developed for smartphones, providing both convenience and pleasure (e.g., angles in pictures and photos can be measured using the smartphone measurement app Partometer). Many people have played such camera measurement tools downloaded from “Google Play” (<http://www.new-itechnologies.com/>, <http://www.vistechprojects.com/>). Above all, to safeguard people’s health, much effort has been directed toward using mobile phone sensing devices for physical examination and environmental monitoring [3–5]. Examples of such sensors include those measuring the ultraviolet index, those used for health monitoring (e.g., heart rate, respiratory rate, and blood oxygen saturation), and those used for air monitoring, ultrasonic scanning, three-dimensional (3D) scanning, and the detection of chemicals.

In this review, the fabrication and application of mobile phone sensors are presented. For example, inertial magnetic sensors, earphones, cameras, and Wi-Fi or 3G all play important roles in mobile phone sensing. Smartphone

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sensors can be classified as electromagnetic sensors, audio frequency sensors, optical sensors, electrochemical sensors, and other sensors. The future development of smartphone sensing and perspectives is also summarized in this review.

2 Representative smartphone sensors

It is well known that material plays an important role in chemical sensing [6–10]. Here, we focus on the study of instruments, especially mobile phone devices. According to different physical principles, we classified mobile phone sensors as electromagnetic sensors, audio frequency sensors, optical sensors (color, image, and spectrum), electrochemical sensors, and other sensors.

2.1 Electromagnetic sensors

Electromagnetic sensors can be used to monitor related electromagnetic signals and even seismic events. Georgiadis et al. [11] built a personal digital assistant (PDA)-based system and monitored electromagnetic signals to predict seismic events. The developed system can connect to the National Observatory of Athens (NOAIG) secure file transfer protocol (SFTP) server using WLAN, GPRS, or UMTS. Figure 1 shows the working process, data storage, and resulting display of the PDA system. Hasen and co-workers [12] built a real-time brain state decoding and 3D reconstruction unit using a smartphone. Meanwhile, Hansen and co-workers [13] captured brain imaging data with a smartphone, reflecting people's everyday social behavior

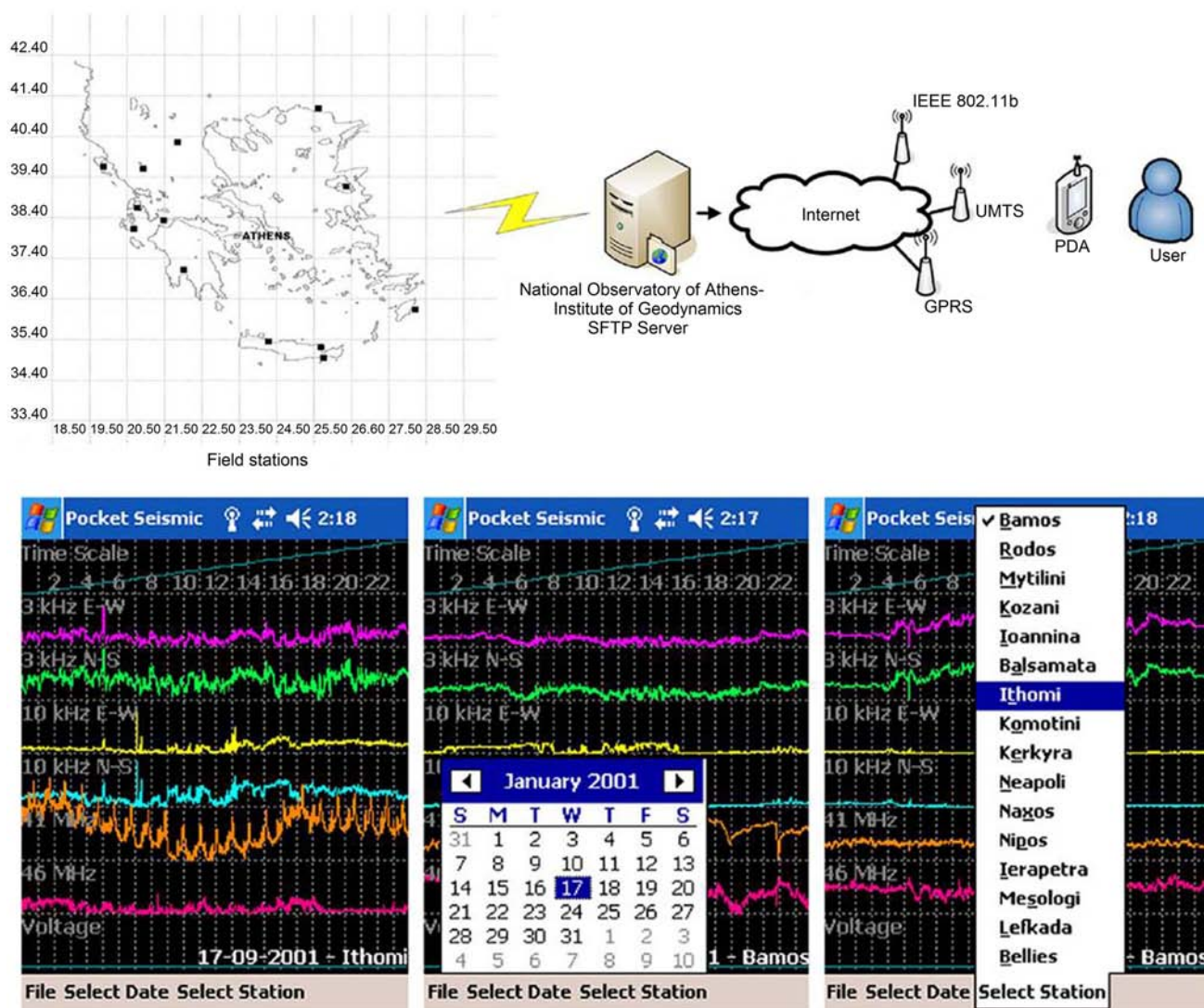


Fig. 1 (Color online) Scheme of the working process, data storage, and display from the PDA system. Reprinted with permission from [11], Copyright 2009, Elsevier

based on a mobile context and a wireless earphone. They claim to be able to distinguish pleasant and unpleasant emotions by using different scalp potentials in pictures and can even replicate results.

2.2 Audio frequency sensors

For indoor and outdoor environmental monitoring, a wearable volatile organic compound (VOC) sensor has emerged [14]. The sensor has high sensitivity and selectivity and rapid response (Fig. 2a, b). The monitoring system contains two major components: a detection unit and a user interface (Fig. 2a). The detection unit is composed of three separate components: a sample collector and conditioner, a sensor array, and a detection circuit. The user interface of the sensor is in a smartphone. The wearable sensor utilizes the resonant frequencies of tuning forks to measure extremely low concentrations of hydrocarbons. The reproducibility of VOC sensors was >81 %, and the

consistency was also acceptable. The mobile phone's audio channel is used to create a layered communications stack. The designed channel can communicate with external devices at a data rate of 8.82 kbps. The harvester delivers 7.4 mW and costs \$2.34 per unit to produce in volumes of 10,000 [15].

2.3 Optical sensors

Optical sensors are based on the use of smartphone cameras. They include colorimetric chemical, optical imaging, and spectroscopy sensing.

2.3.1 Colorimetric chemical sensors

Capitán-Vallvey and co-workers [16] exported a mobile phone platform for portable chemical analysis. The platform can detect ion concentrations by capturing an image and obtaining its characteristic H (hue) value, as shown in

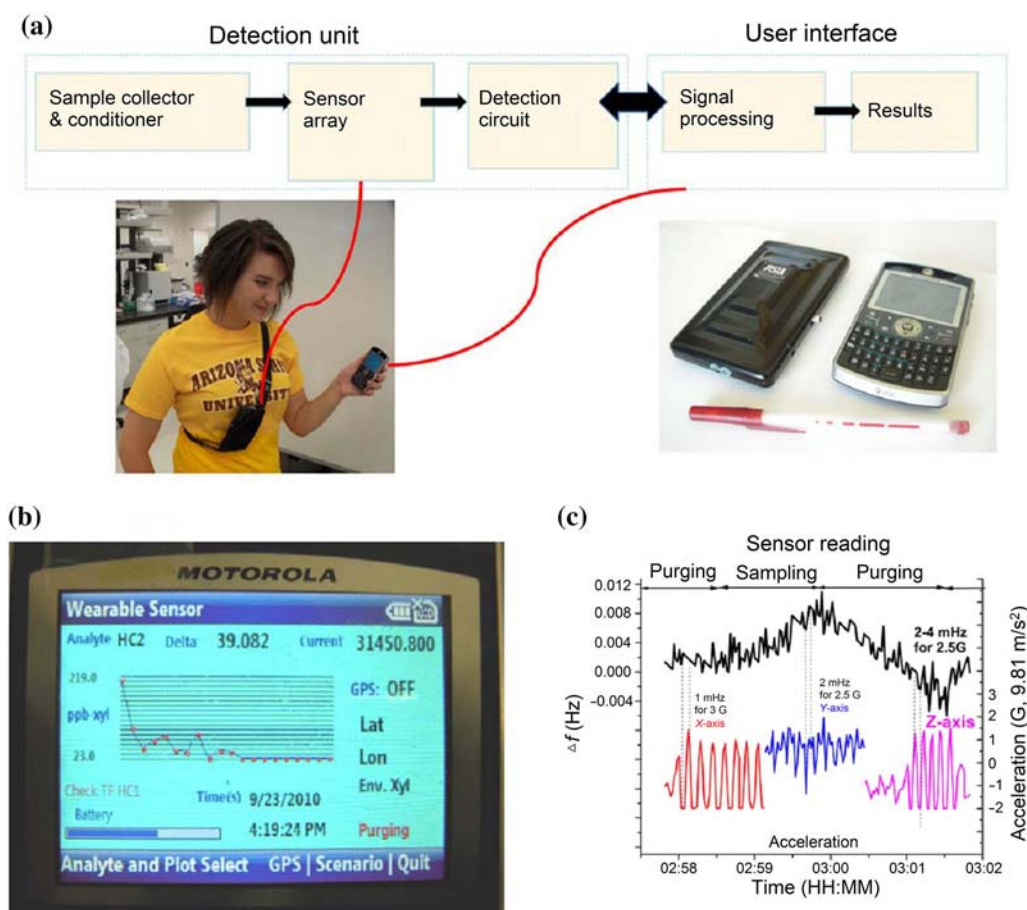


Fig. 2 (Color online) Wearable VOC sensor components and pictures. **a** User interface. **b** Robustness test. **c** Sensor output. Reprinted with permission from [14], Copyright 2012, Elsevier

Fig. 3. Such a platform allows an unprofessional user to detect potassium concentration in water. The presented platform has a detection limit of 3.1×10^{-5} mol/L, a wide linear range from 3.1×10^{-5} to 0.1 mol/L, and a high reproducibility of $<1.6\%$ for potassium determination. Further, they presented a portable instrument for the determination of gaseous oxygen [17]. Measurement of pH from 1 to 12 was also accomplished on a mobile phone by Papautsky and co-workers [18]. They also achieved diagnostic assays with high accuracy by using a smartphone in a wide range of ambient conditions.

Chlorine concentration can also be detected by a mobile phone sensor [19]. In such a system, a self-referencing configuration contains two image regions (the reference material and the detecting sample), and the specific color ratio from the above two image regions is used to indicate its corresponding chlorine concentration. The detection limit is 0.3 ppm (1 ppm = 1 mg/kg) with $<7\%$ measurement errors. Choodum et al. [20] used the camera of a smartphone to quantitatively test for the amount of trinitrotoluene (TNT) in soil. The linear range of TNT concentration is from 1 to 500 mg/L with a low relative error from 0.4% to 6.3%. In their analysis over 4 d, similar relative errors of 0.4%–6.2% and good precision (2.09%–7.43% relative standard deviation) were also observed for spiked soil.

Besides the above applications in environment detection, colorimetric chemical sensors can also be used for health examination. For example, Ozcan and co-workers [21]

imaged and analyzed albumin in urine on a smartphone by using fluorescent assays. The digital sensing platform, weighing approximately 148 g, employs fluorescent assays using an albumin tester (Fig. 4). The detection limit is about 5–10 $\mu\text{g/mL}$ in buffer and urine samples. They developed a platform named iTube for personalized food allergen testing. It can sensitively detect allergens in food samples by imaging and automatically analyzing colorimetric assays. The weight of iTube is only 40 g and can be installed on the existing camera unit of a smartphone [22]. They also built a rapid-diagnostic-test (RDT) reader platform that could work with lateral flowing immunochromatographic assays. Various types of RDTs can be designed and developed to achieve different molecular detections, such as for malaria, tuberculosis (TB), and human immunodeficiency viruses (HIV RDTs) [23].

In addition, a smartphone can quantify vitamin D levels rapidly [24]. The test strip was made by using a novel gold-nanoparticle-based immunoassay, allowing colorimetric detection of vitamin D at physiological levels. The accuracy of the platform is better than 15 nmol/L with a precision of 10 nmol/L. Erickson and co-workers [25] developed a platform for Kaposi's sarcoma-associated herpesvirus (KSHV) nucleic acid detection on a smartphone. Their final device can detect DNA sequences from KSHV down to 1 nmol/L. Hong and Chang [26] developed a practical app for immediate point-of-care (POC) multi-analyte sensing by using only a smartphone. Their diagnosis results made by using the app of the contents of

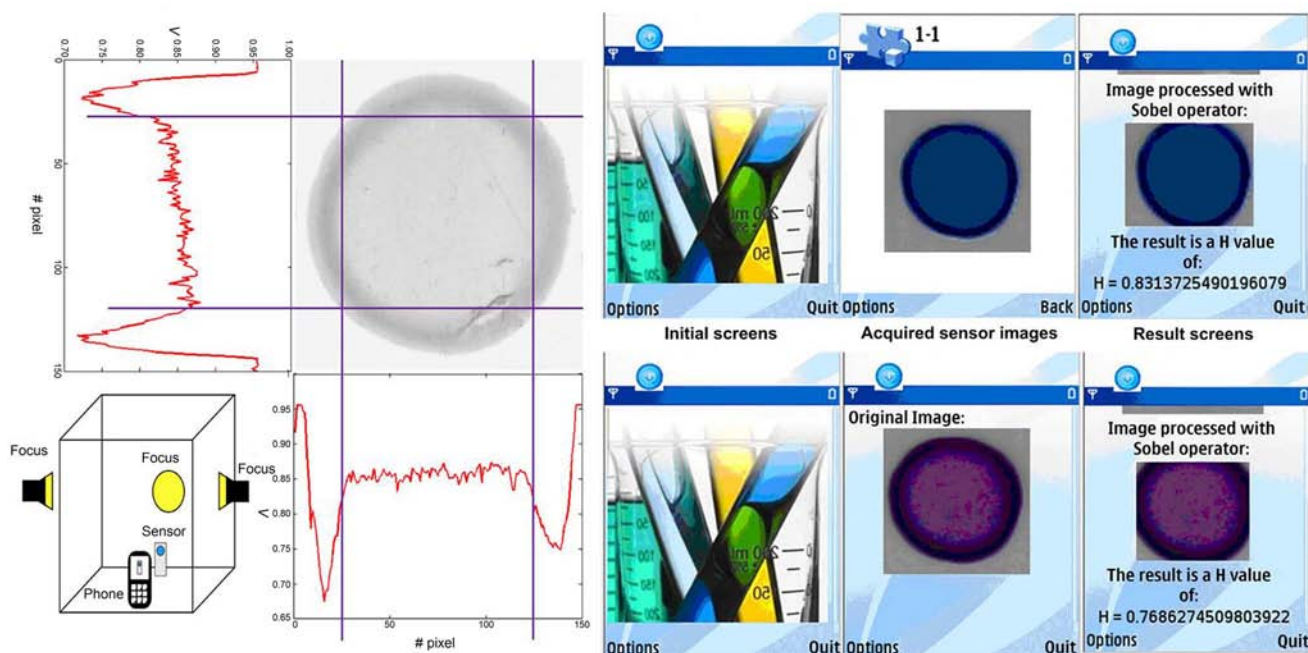


Fig. 3 (Color online) Scheme of mobile phone platform for potassium detection and screen captures of the software application. Reprinted with permission from [16], Copyright 2011, Elsevier

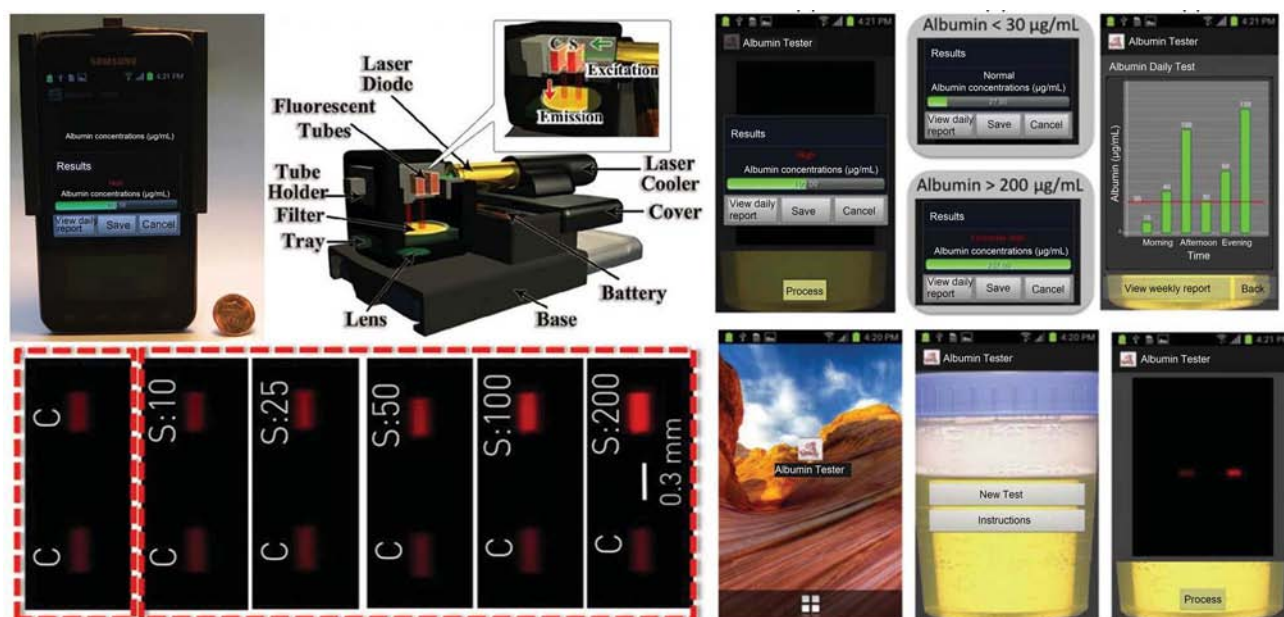


Fig. 4 (Color online) Photographs of the albumin tester installed on a smartphone shown from different views, screen shots of the albumin tester application running on a mobile phone, and quantification of the urinary albumin concentration. Reprinted with permission from [21], Copyright 2013, the Royal Society of Chemistry

ascorbic acid, leukocyte, glucose, nitrite, ketones, protein, urobilinogen, bilirubin, and red blood cells in urine are consistent with those obtained by using a commercial urine analyzer. Mitra and co-workers [27] developed a rapid, low-cost water-monitoring sensor termed Mobile Water Kit (MWK). The MWK can simultaneously detect total coliform and *Escherichia coli* (*E. coli*) bacteria in contaminated drinking water. With this MWK, the total coliform and *E. coli* bacteria in water samples can be detected within 30 min. For one of the field samples, the MWK was even able to detect the total coliform within 35 s.

2.3.2 Optical imaging techniques

Ozcan and co-workers [28] proposed lens-free digital microscopy on a smartphone for the first time. The weight of the lens-free imaging platform is 38 g. It is attached to the camera of a smartphone, which catches images of various-sized microparticles and biological cells. Another application of optical imaging is a smartphone-based *E. coli* detection platform for screening liquid samples [29]. By using battery-powered LEDs, these labeled *E. coli* particles are captured on a capillary surface. The detection limit of this platform is about 5 to 10 CFU/mL in buffer solution and in fat-free milk. To create new opportunities, especially for telemedicine applications, imaging cytometry and fluorescent microscopy have been integrated on a smartphone (Fig. 5) [30]. The system has a spatial

resolution of $\sim 2 \mu\text{m}$ for the obtained images. This resulting imaging flow cytometer could be potentially used in sensitive imaging of bodily fluids and remote screening of water quality. Moreover, the density of red blood cells, white blood cells, and hemoglobin in human blood samples was captured by using separate optical attachments to the smartphone [31].

In their next work, Ozcan and co-workers [32] further developed wide-field fluorescent and dark-field microscopy on a smartphone. The weight of the designed optical attachment is only $\sim 28 \text{ g}$. The resolution of the microscopy is $\sim 10 \text{ mm}$ over a field of view (FOV) of $\sim 81 \text{ mm}^2$. Then, they summarized some of the recent work in emerging computational imaging, sensing, and diagnostic techniques [33, 34]. Recently, they fabricated an RDT reader platform termed Google Glass [35]. Various lateral flow immunochromatographic assays and similar diagnostic tests (e.g., HIV and quantitative prostate-specific antigen (PSA) tests) can be conducted by using Google Glass. This smart RDT application could be quite valuable for epidemiology, mobile health, and telemedicine applications.

Lee and Yang [36] developed a portable chip-scale lensless microscopy device used in mobile healthcare and environmental monitoring. The light source of this device is ambient illumination. A common-built Android application is used to acquire and reconstruct images, including blood smear images, freshwater green algae images, and microsphere images (Fig. 6). To improve the sensitivity of

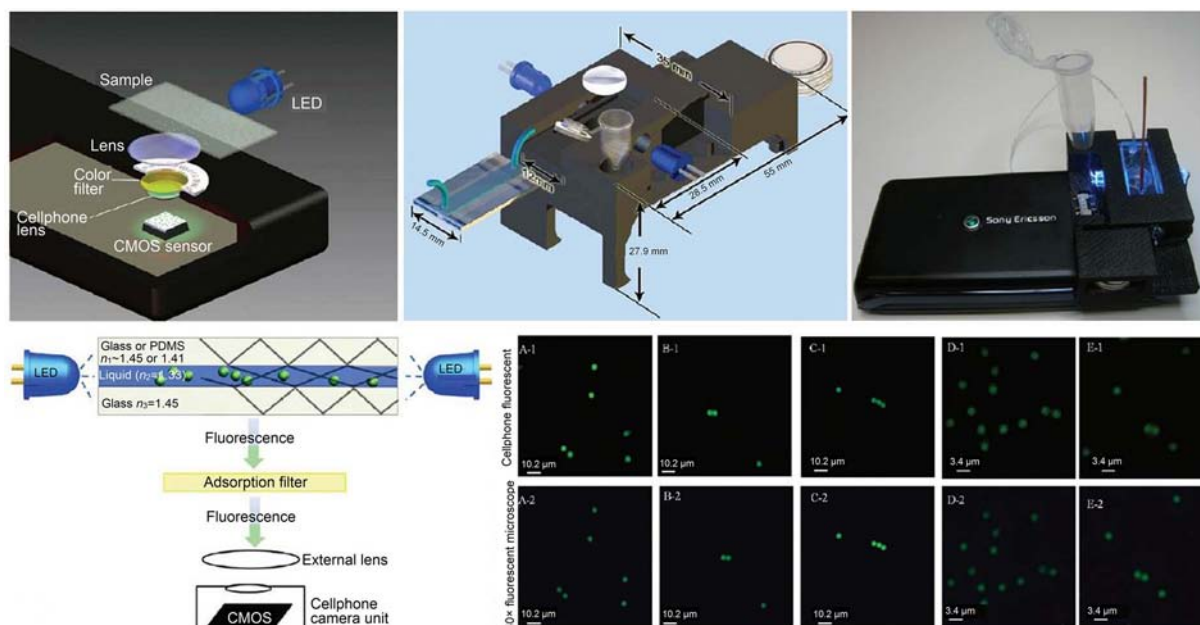


Fig. 5 (Color online) Scheme of the designed optical attachment on a smartphone and images obtained by a fluorescent imaging cytometer. Reprinted with permission from [30], Copyright 2011, American Chemical Society

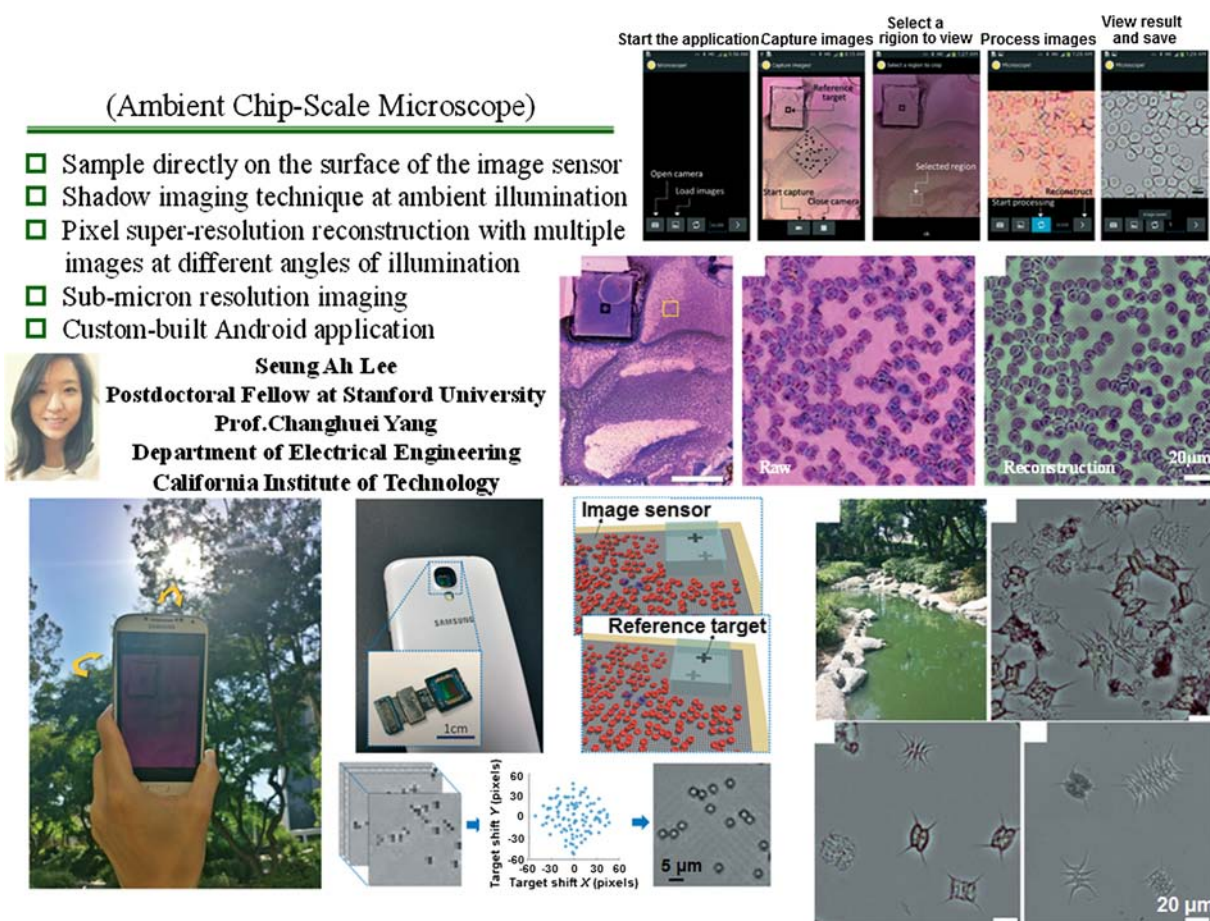


Fig. 6 (Color online) Working principle, photographs, and detection results of the smartphone-based chip-scale microscope. Reprinted with permission from [36], Copyright 2014, the Royal Society of Chemistry

mobile phones, Rasooly and co-workers [37] proposed a capillary tube array to amplify fluorescence signals. Its sensitivity ranges from 1,000 to 10 nmol/L, and it uses a 36-capillary tube array. Moreover, they proposed a novel computational image stacking approach, enabling another factor of ~ 10 increase [38]. A dual-wavelength fluorescent sensor was built to measure components of a basic metabolic panel with a point-of-care device [39].

2.3.3 Spectroscopy sensing

Preechaburana et al. [40] proposed chemical sensing on smartphones by using surface plasmon resonance (SPR) spectroscopy. The light source is supplied by an image displayed on the smartphone screen. A disposable optical element is made of polydimethylsiloxane rubber and epoxy with a refracting index matching that of glass. When the measured noise level in the primary signal is 0.31 %, the resolution of the platform is 2.14×10^{-6} refractive index unit (RIU) (1×10^{-6} RIU for commercial SPR devices). A fiber optic SPR biosensor based on smartphone platforms was made by connecting the lightweight optical

components and sensing element using optical fibers [41]. It is worth mentioning that Cunningham and co-workers [42] have made a label-free photonic crystal (PC) biosensor attached to a glass microscope slide of a smartphone. As shown in Fig. 7a, broadband light is collimated by an entrance pinhole and a collimating lens, passes through a linear polarizing filter, and then passes through the PC. The camera collected the light enhanced by a cylindrical lens, and a software app was used to convert the camera images into the PC transmission spectrum (Fig. 7c and d). The accuracy of PC resonant wavelength is 0.009 nm obtained by a curve-fitting analysis. Salmonella can also be successfully detected on a smartphone by using Mie scattering through a spectrometric benchtop system [43], with a detection limit of 10^2 CFU/mL and a linear range up to 10^5 CFU/mL.

2.4 Electrochemical sensors

As reported, a portable “Chip EIA (enzyme immunoassay)” can make enzyme-linked immunosorbent assay (ELISA) more suitable for point-of-care testing [44]. In

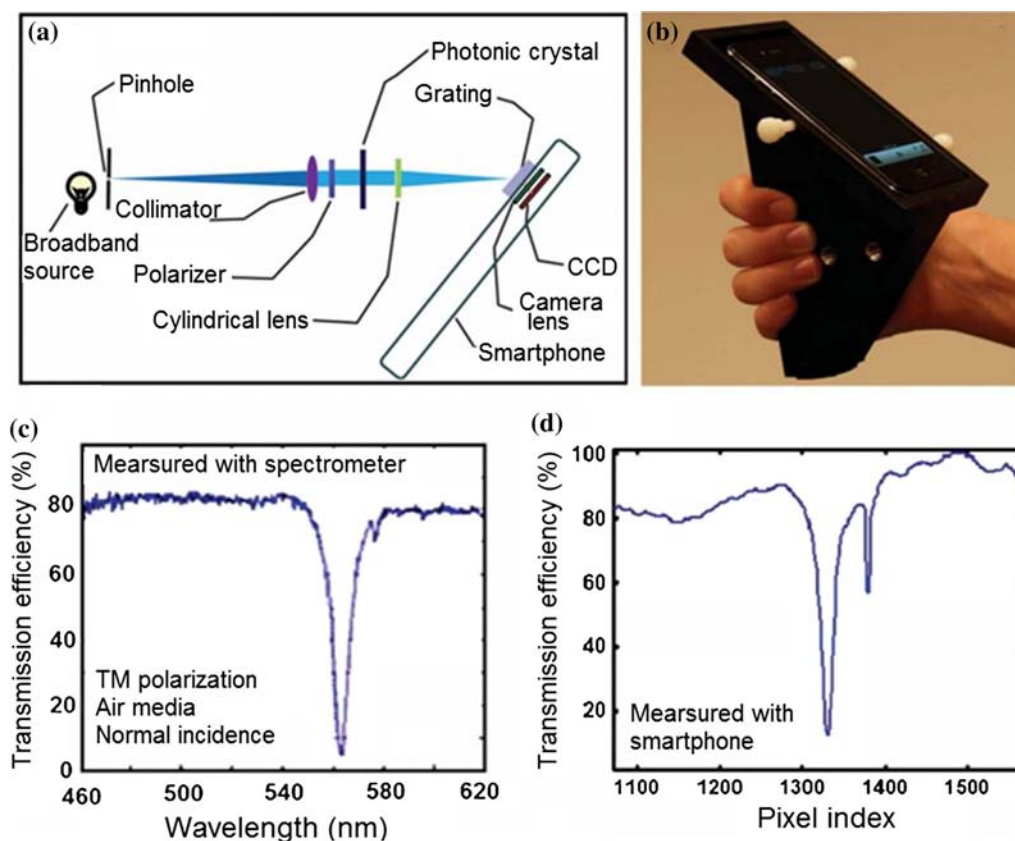


Fig. 7 (Color online) **a** Scheme of the optical components within the smartphone cradle. **b** Photograph of the cradle with a PC biosensor slide. **c**, **d** The analogous spectrum obtained by using the spectrometer smartphone detection system. Reprinted with permission from [43], Copyright 2013, the Royal Society of Chemistry

comparison with conventional microtiter plate ELISA, this Chip EIA does not need a power supply as it utilizes a simple permanent magnet and magnetic nanoparticles. The cost of the chip for total prostate-specific antigen detection is estimated at \$6.00. In 2013, Ho and co-workers [45] presented another platform for rapid, quantitative biomolecular detection on a mobile phone. As shown in Fig. 8, this system contains a signal processing and data analysis circuit, disposable microfluidic chips, and a phone. This portable device can detect *Plasmodium falciparum* histidine-rich protein 2 (PfHRP2), and a simple detection takes only 15 min with two loading steps. The detection limit of the system is 16 ng/mL in human serum.

Besides application in biological sciences, smartphone electrochemical sensors can be utilized in industry and environment analysis. For example, a potentiostat was built using a mobile phone programmed with suitable software [46]. The maximum peak voltage of the potentiostat was ~ 1.77 V, which can generate electrochemiluminescence (ECL) from the $\text{Ru}(\text{bpy})_3^{2+}$ system. Huang and Ugaz [47] have also detected label-free biomolecules and chemical reagents by using smartphone optics. Another low-cost ECL sensor using a mobile

smartphone is described in Ref. [48]. López et al. [49] presented a pH, NH_4^+ , and temperature wireless sensor network for a fish farm. In addition, Othman and Shazali [50] reviewed wireless portable sensors applied in environmental monitoring.

The most representative work, appearing in 2014, was conducted by Whitesides and co-workers [51], who constructed a simple, affordable, handheld device that can perform almost any electrochemical analysis and transmit the results to the cloud from any phone, over any network, from any location. The electroanalytical techniques include chronoamperometry, cyclic voltammetry, differential pulse voltammetry, square wave voltammetry, and potentiometry. To confirm its performance, the device was used in four applications: (1) to measure glucose in human blood, (2) to measure sodium in urine for clinical analysis, (3) to measure trace heavy metals (lead, cadmium, and zinc) in water, and (4) to measure a malarial antigen for clinical research (Fig. 9).

We have developed an electrochemical sensor, consisting of a homebuilt electrochemical workstation and a mobile phone programmed with specific software. To verify the performance of our device, alcohol concentrations in a

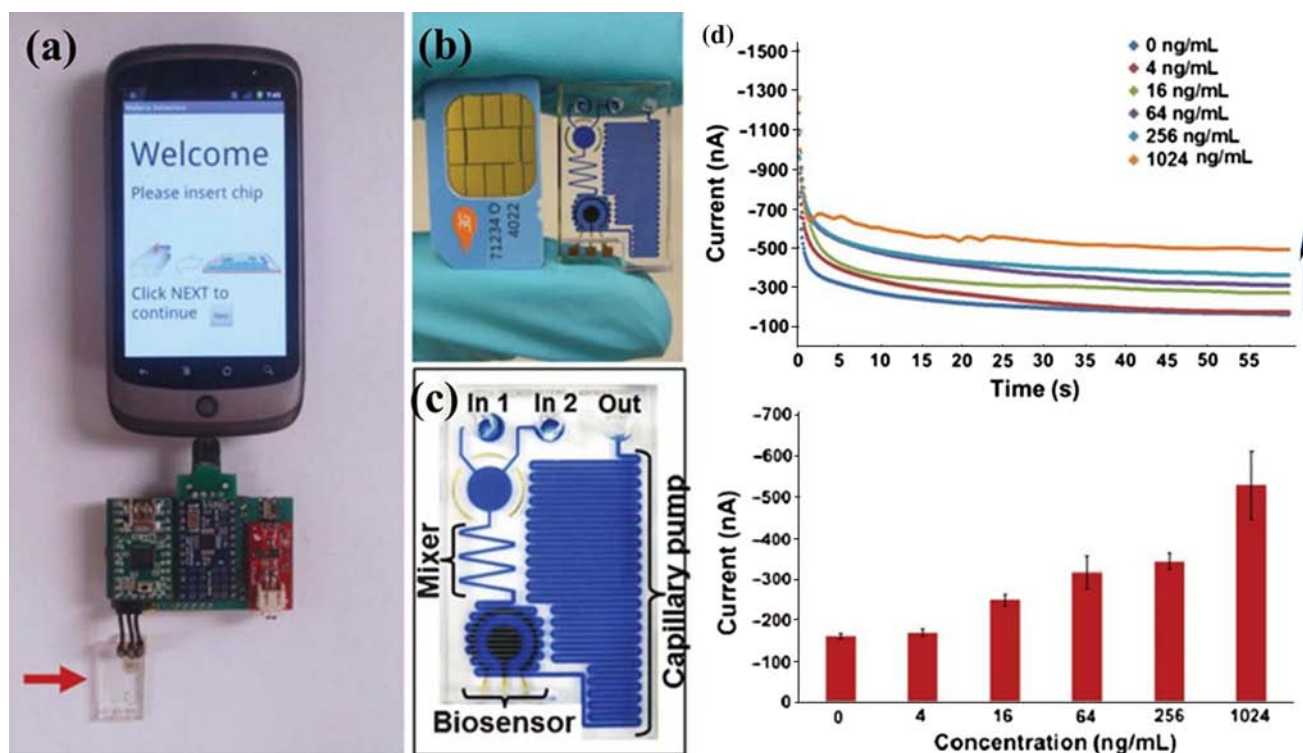


Fig. 8 (Color online) **a** Photograph of the assembled prototype device. Photograph **(b)** and an enlarged image **(c)** of the chip. **d** Electrochemical detection of PfHRP2 antigen in human serum. Reprinted with permission from [45], Copyright 2013, the Royal Society of Chemistry

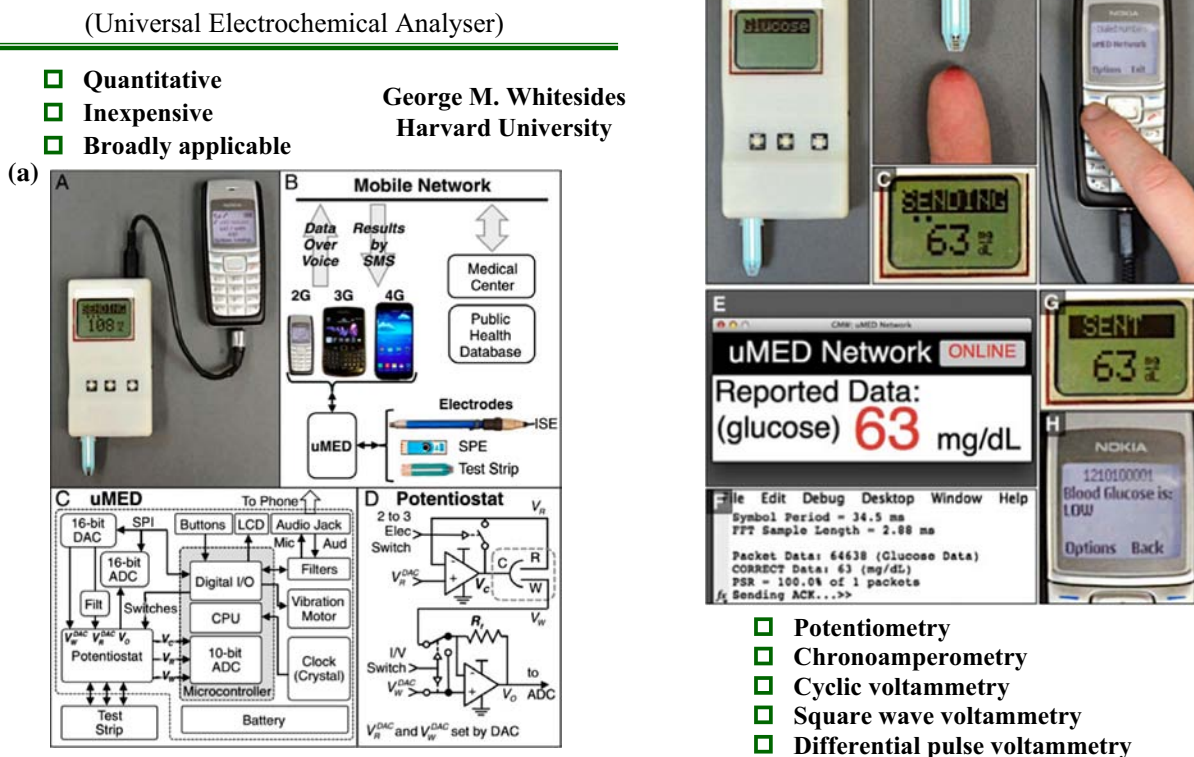


Fig. 9 (Color online) **a** Image and schematic of the universal mobile electrochemical detector (uMED). **b** Demonstration of the uMED network in operation. Reprinted with permission from [51], Copyright 2014, American Chemical Society

standard solution, human blood, and breath were studied (Fig. 10). An electrochemical Alco tester was fabricated by using a disposable electrode modified by biological polyvinylchloride-g poly-*N*-vinylpyrrolidone polymer film (PVA-g-P(4-VP)) containing alcohol oxidase (–AOx). The dissolved oxygen can be reduced at a certain potential to generate a current (i^0) on the Alco tester. After the addition of alcohol, it is oxidized to aldehyde under the catalysis of AOx, while oxygen is reduced to hydrogen peroxide. The current of oxygen reduction decreases with the increase in alcohol concentration, so a specific relationship between the current value and alcohol concentration can be obtained. The detection limit of the Alco tester is 0.1 mg/mL. Bisphenol A, different ions (K^+ , Na^+ , Ca^{2+} , Mg^{2+} , etc.), and various gases (CO , CO_2 , H_2S , SO_2 , and formaldehyde) were also detected by using this smartphone device.

2.5 Other sensors

There are some other sensors based on smartphone technology that have been developed. For example, Li et al. [52] developed sensing modules embedded in an iPhone for chemical detection. These resulting mobile devices have been used to detect ammonia and chlorine at ppm

concentration. To centralize the chemical sensing results at different locations, they built a network cloud for their 29-phone sensors. An accurate spirometer (called SpiroSmart) was also built on a smartphone [53]. The mean error in comparison with a clinical spirometer is 5.1 % in common measures, as shown in Fig. S1 (online). Although SpiroSmart cannot replace a clinical spirometer, it may be an alternative for many handheld monitors and home spirometers.

3 Conclusions and perspectives

Mobile phone instrumentation and its measurement applications have developed considerably in the past decade as a consequence of the emergence of new technologies. This development has taken place for two principal reasons: (1) More and more physical quantities can be measured by new embedded sensors on a smartphone and (2) wider wireless and wired connection possibilities and smart visual interfaces are available to transmit measurement results. A variety of mobile phone sensors have been developed and applied in daily life. We classified these sensors as electromagnetic, audio frequency, optical (color, image, and

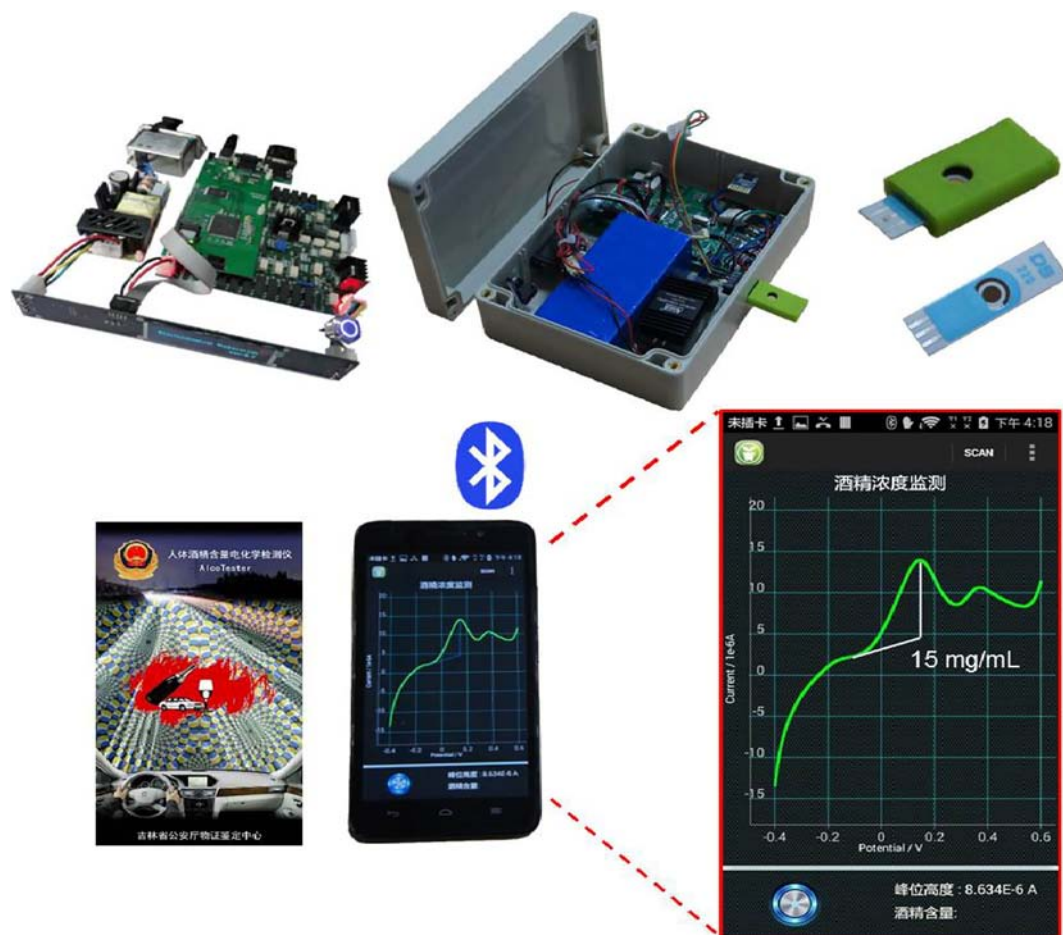


Fig. 10 (Color online) Photographs of our homebuilt mobile electrochemical workstation and Alco tester and the detection result of alcohol in human breath

spectrum), electrochemical, and other. We should realize that the measurement error of such sensors is in general larger than that of conventional methods. Nonetheless, such mobile sensors can still provide a good alternative for many handheld monitors and home spirometers.

The development of smartphone sensing depends on different technologies (microelectronics, software, and communications) (<http://www.mckinsey.com>). In the future, mobile phone devices will benefit from (1) having better operating systems to achieve data acquisition and processing by inexperienced users, (2) improvements in access point technology for increased power processing and reduced power consumption, (3) improved smart display technology with more power efficiency and flexibility, (4) new sensor types being integrated into smartphones to acquire various new physical quantities, (5) faster battery charging, wireless battery charging, and adaptive battery management, (6) advances in material technology to enable a new generation of lighter, more flexible, and durable devices, (7) trends in Web technology to make data transformation more universal, convenient, and rapid, (8)

expansion of cloud service to permit online data storage and data sharing between different users, (9) the development of user interfaces that can use gestures and retina tracking, an infrared keyboard, and context-aware user interfaces, and (10) faster and safer mobile network capabilities.

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Conflict of interest The authors declare that they have no conflict of interest.

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Fig. S1 Subjects using SpiroSmart (left) and a clinical spirometer (right) with their corresponding example curves. (The images have been downloaded from the websites <http://www.medgadget.com/2012/09/spirosmart-iphone-app-accurately-estimates-lung-air-volume-video.html>; <http://www.webpronews.com/spirosmart-app-turns-your-iphone-into-an-accurate-spirometer-2012-09>; and <http://ubicomplab.cs.washington.edu/wiki/SpiroSmart>.)