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A novel sensing chip with dual-coil inductance for determining raw milk quality

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ABSTRACT

This paper presents a novel inspection method that uses dual-coil inductance to evaluate the quality of raw milk. The device principally contains a silicon-based chip with two co-planar coils, which is fabricated using a simple microelectroplating process. When the coils are entirely immersed in raw milk and a specific alternating electrical signal is applied to one of the coils, the other coil induces a phase-shifted electrical signal because of the effect of eddy currents. Using the phase variation between both coils, the quality of the raw milk, in terms of the somatic cell count (SCC), can be evaluated, because the milk from a cow that suffers from mastitis is a better conductor of electric current. In this study, the characteristics of the magnetic inductance for a specified coil design and its sensing performance are simulated and evaluated using COMSOL software and by experiment. The experimental results show that higher SSCs cause larger phase shifts. This shift increases as the excitation frequency is increased. For a typical fabrication result, using a sensing coil with 25 loops, the measurement sensitivity in terms of SCC is 3°/log(SCC) at an excitation frequency of 9 MHz. The proposed dual-coil chip reduces size and cost and has a rapid response, which allows efficient quality inspection of raw milk.

1. Introduction

Economic milk production requires high milk yield and quality from each cow. However, some diseases cause considerable damage to cattle and reduce the quantity and quality of the milk produced. The single most costly disease for the dairy industry worldwide is mastitis, which is an inflammation of the mammary gland. When bacteria infect an area, the cow's immune system responds to counter the infection by increasing the number of somatic cells in the milk. Mastitis is generally classified as clinical or subclinical, depending on the degree of inflammation. Clinical mastitis is characterized by an acute inflammation of the udder and causes a sharp decrease in milk yield. Subclinical forms of the condition can remain undetected but still cause a significant decrease in milk production. This affects the dairy farmer financially through reduced milk yield, the cost of treatment and drugs, wasted milk, and culling [1,2].

In determining the degree of mastitic infection in raw milk, the somatic cell count (SCC) is the most widely accepted criteria that is used to quantify milk quality because milk from cows that are infected with mastitis generally has a higher somatic cell count than milk from uninfected cows. It is associated with the degree of development of mastitis in the cows. In general, the higher the count, the lower the quality of the milk. A dairy industry rule of thumb states that cows that have less than 2×10^5 SCC/ml of milk are considered healthy or only slightly infected with mastitis. A higher SSC can significantly reduce milk yield and increase treatment costs, so milk testing and quality control are essential if the milk processing industry is to protect raw milk from the risk of contamination by bacteria and other substances [3,4].

The commercial methods that are used to estimate SCC include the California mastitis test (CMT), a direct microscopic count (DMC) and a fossomatic cell count (FSCC) [5]. However, these methods have their own limitations in terms of cost, accuracy and the time that is required for sample pretreatment. In particular, an artificial error in the CMT and DMC is a significant problem when SCC is to be determined. The FSCC requires expensive equipment and is only suitable for commercial or large-scale laboratories, although it is a simple cow-side indicator of the SCC for milk and is a useful technique for detecting subclinical mastitis. Currently, several screening techniques to evaluate somatic cell counts use fluorescence analysis [6,7], near-infrared spectroscopy (NIRS) [8], electrical conductivity [9–11] and relative permittivity measurements [12,13]. Fluorescence analysis methods are using emitted light to label each cell and then to determine the SCC for raw milk using an electric pulse that is emitted by each dyed

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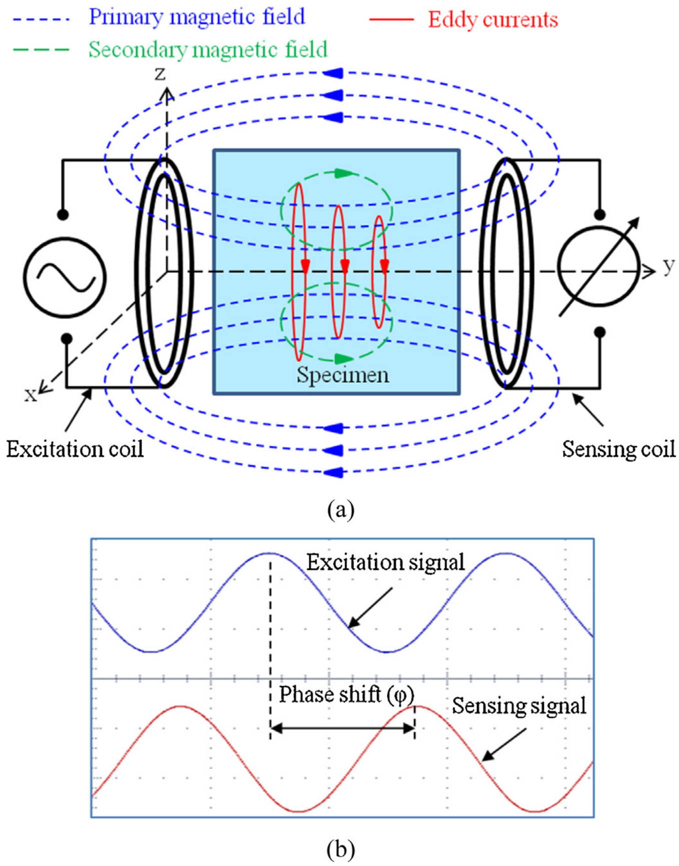

Fig. 1. The SCC sensing principle using a dual-coil inductance: (a) a simplified model of the proposed method and (b) the diagram of input and sensing signals.

cell. The determination of the SCC using a near-infrared spectrum uses the related changes in milk composition. The others, which use the electrical conductivity and relative permittivity, use the different electrical properties of infected and healthy animals to detect the SCC. Generally, milk from a cow that is affected by mastitis is a better conductor of electric current than that from a healthy cow because there is an increase in Na^+ and Cl^- ions and a decrease in K^+ ions and lactose [14]. However, these methods still require expensive facilities and complex sample pretreatment and are not easily accessible for emerging small-scale processors.

As these studies show, milk usually has a specific electrical conductivity and there is a positive relationship between the electrical conductivity of milk and the SCC. In addition, its relative electrical permittivity is also changed when the SCC varies. Therefore, this paper presents a novel method with a co-planar dual-coil to determine the SCC for raw milk that uses a simple silicon-based microfabrication and the mechanism of mutual inductance. The phase differences between the excitation and the sensory electrical signals are used to determine the SSC for raw milk. Although inductive sensors based on change in the self inductance of a sensing coil as a function of change in a measurement are widely used in industry, the output corresponding to change in inductance will be very small. Typically the variation in coil inductance is in the range 5–10% of the offset inductance [15]. The use of mutual inductances was the ease with which a high degree of sensitiveness may be obtained and the possibility of calculating the mutual inductance from the physical dimensions and thereby having absolute values [16]. In this study, the magnetic field of the dual-coil inductance and the performance of the SCC inspection chip are evaluated using commercial simulation software and by experiment. The proposed

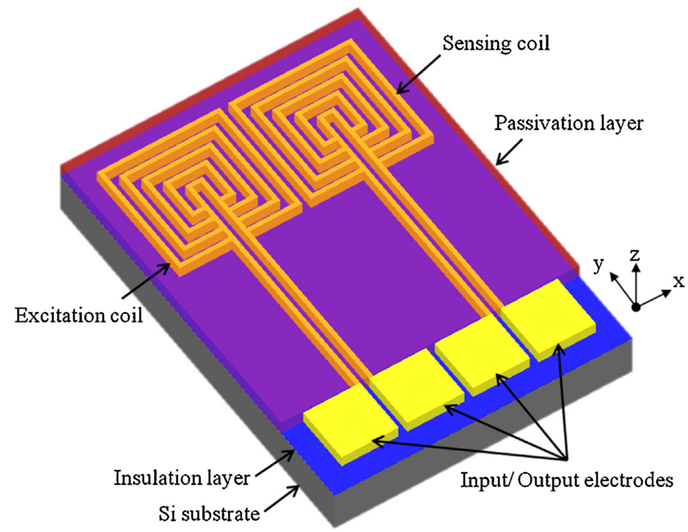

Fig. 2. A schematic view of the proposed SCC sensing chip with a dual-coil inductance.

sensing chip allows early identification of mastitis and has specific biochemical applications.

2. Design and analysis

2.1. Design concept

The sensing mechanism for the proposed chip uses a dual-coil inductance to determine the quality of raw milk, as shown in Fig. 1, using the principle of magnetic induction tomography (MIT). When

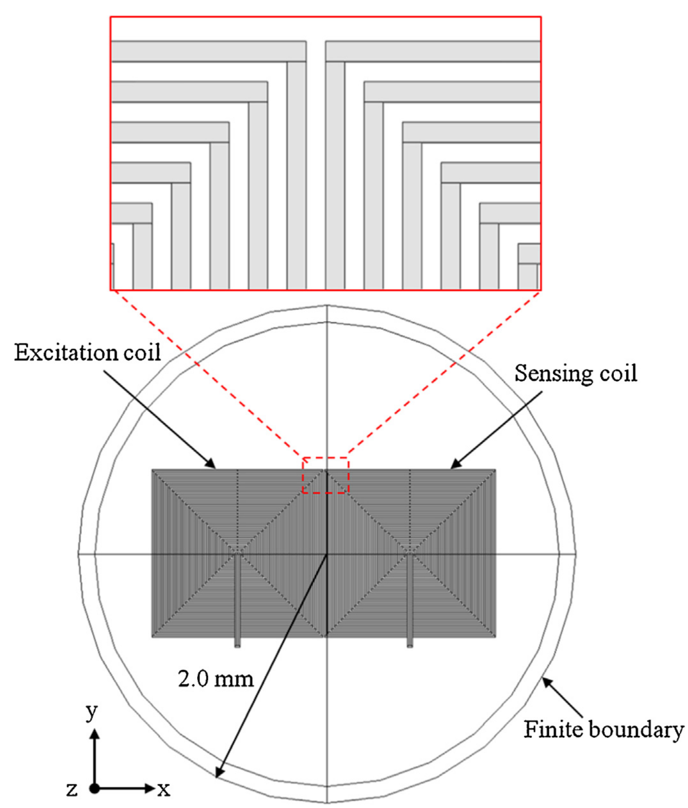

Fig. 3. A 3-D analytical model of the dual-coil inductance.