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Characteristics of Cobalt Ohmic Contacts Fabricated on Silicon Surface by Laser-Induced Diffusion

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Abstract
This study investigates the fabrication and characterization of cobalt Ohmic contacts on n-type silicon substrates using laser-induced diffusion. A Q-switched Nd:YAG laser was used to provide a low thermal budget method for forming a conductive $CoSi_2$ layer. Results demonstrate a critical relationship between the number of laser pulses and the electrical properties of the contact. A significant decrease was observed in sheet resistance and a corresponding increase in electrical conductivity up to an optimal number of pulses. This is attributed to the enhanced diffusion and activation of dopant atoms, leading to a high concentration of free charge carriers. However, excessive laser pulses beyond this optimal range result in a degradation of electrical properties, as evidenced by a rise in sheet resistance. This is due to the formation of crystallographic defects that act as scattering centers, thereby reducing carrier mobility. The findings underscore the importance of precise process control to achieve high-performance Ohmic contacts while avoiding thermal damage.

Keywords: Laser-induced diffusion; Ohmic contacts; Cobalt dopants; Silicon devices
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1. Introduction

Ohmic contacts are essential in microelectronics and integrated circuits, ensuring efficient and reliable operation. An Ohmic contact is a low-resistance electrical junction between two materials, typically a metal and a semiconductor, that follows Ohm's law. This means the current flowing through the contact is directly proportional to the applied voltage, and the current-voltage (I−V) characteristic is linear and symmetric [1-3]. Unlike rectifying contacts (Schottky contacts), which have a non-linear I−V curve, Ohmic contacts allow current to flow equally well in both directions with minimal voltage drop. This is crucial for connecting various components like transistors, resistors, and capacitors within a chip [4-6]. Without a proper Ohmic contact, the resistance at the junction would be high, leading to significant power dissipation as heat, reduced signal integrity, and slower device performance [6]. The process of forming these contacts often involves doping the semiconductor heavily at the interface or using specific metal alloys that create a minimal energy barrier [8-10]. By ensuring a low-resistance path for charge carriers, Ohmic contacts enable the high-speed switching and data transfer required for modern microprocessors, memory chips, and other complex integrated circuits, thereby forming the fundamental plumbing of all electronic devices [11-13].

Fabricating Ohmic contacts with low resistance is critical for all semiconductor devices. The process typically begins with meticulous cleaning of the semiconductor surface to remove native oxides and other contaminants that can form a high-resistance barrier. This is often achieved using wet chemical etches or plasma treatments. After cleaning, a metal layer is deposited onto the designated contact areas, usually through techniques like sputtering or evaporation [14-16]. The choice of metal is crucial, as it must have a work function that is either higher than the semiconductor's for p-type material or lower for n-type material, to facilitate low-resistance tunneling. The most critical step is often a high-temperature annealing process, such as rapid thermal annealing (RTA). During annealing, the metal and semiconductor atoms interdiffuse, forming a metal-semiconductor alloy or silicide layer. This highly doped and intermixed interface reduces the Schottky barrier height and creates a low-resistance pathway for charge carriers, which is the defining characteristic of an Ohmic contact. For specific applications like those in high-power devices, more advanced techniques like laser annealing are sometimes used to achieve localized heating and minimize thermal damage to the surrounding components [17-19].

Laser-induced diffusion, often referred to as laser annealing or laser doping, is an advanced method for fabricating Ohmic contacts [20]. The process involves using a high-energy laser pulse to melt a very thin, localized region of the semiconductor surface. This rapid, localized melting allows dopant atoms (either pre-deposited or from a surrounding gas) to diffuse into the semiconductor at concentrations that can exceed the normal solid solubility limits [21-23]. The subsequent ultrafast cooling and solidification, known as liquid phase epitaxy, results in a heavily doped, high-quality crystalline layer directly beneath the metal contact. This heavy doping reduces the width of the Schottky barrier at the metal-semiconductor interface, enabling a low-resistance Ohmic contact primarily through field emission tunneling [24,25].

The advantages of this technique are significant. It provides a low thermal budget process, meaning the bulk of the semiconductor wafer remains at or near room temperature, which is crucial for modern integrated circuits with temperature-sensitive materials or complex layered structures. This localized heating also allows for the selective formation of contacts in specific areas without affecting nearby components [26-28]. Furthermore, it can achieve extremely high dopant concentrations, leading to exceptionally low contact resistances, which is particularly beneficial for wide-bandgap semiconductors like gallium nitride (GaN) and silicon carbide (SiC), where forming good Ohmic contacts is notoriously difficult [29-31].

However, the method is not without its disadvantages. The rapid heating and cooling cycles can induce thermal stress and crystallographic defects, such as dislocations or cracks, which can degrade device performance if not carefully controlled. The process parameters—laser energy density, pulse duration, and wavelength—must be precisely optimized for each material system to avoid surface damage. It can also be more complex and expensive than conventional rapid thermal annealing (RTA) for large-scale, uniform fabrication [32-34].

Despite these challenges, recent achievements have demonstrated the immense potential of laser-induced diffusion. Researchers have successfully used it to create high-quality, low-resistance Ohmic contacts on materials like GaN and SiC, which are critical for next-generation power electronics and UV LEDs. For example, studies on GaN have shown that laser irradiation can create nitrogen vacancies, which enhance tunneling and reduce contact resistance [35,36]. Similarly, this technique has been used to form Ohmic contacts on p-type ZnO, a material that has been difficult to dope, paving the way for its use in p-n homojunction devices.[7] The ability to achieve ultra-shallow, high-concentration doping with minimal thermal impact makes laser-induced diffusion a promising and actively researched method for fabricating high-performance semiconductor devices [37-39].

Using cobalt to form cobalt silicide ($CoSi_2$) as an Ohmic contact on silicon substrates is a widely used and well-established technique in microelectronics, particularly in older CMOS technologies (like the 130 nm node) [40--42]. A significant advantage is its low electrical resistivity, which ensures a minimal voltage drop and power loss across the contact. This is crucial for high-speed circuits where signal integrity is paramount [43,44]. The silicide formation is a self-aligned process (known as salicidation), which simplifies fabrication by creating contacts only where the cobalt and silicon are in direct contact, without complex lithography steps. This enables smaller, more uniform contacts, which are essential for device scaling [45]. Cobalt silicide also exhibits good thermal stability, making it compatible with subsequent high-temperature processing steps. However, a major disadvantage is the potential for "silicide spiking" or junction penetration, where the silicide layer grows too deeply into the shallow junctions of the silicon substrate, causing a short circuit between different device regions and leading to device failure. This issue is particularly problematic as device dimensions shrink and junctions become shallower [46,47]. Another drawback is the mechanical stress induced by the rapid thermal processing, which can lead to film cracking or delamination, affecting the contact's long-term reliability [48,49].

In this work, the fabrication and characterization of cobalt Ohmic contacts on n-type silicon substrates using laser-induced diffusion is presented. The relationship between the number of laser pulses and the electrical properties of the contact are introduced.

2. Experimental Work

Preparing an n-type (111) silicon substrate for Ohmic contact experiments using laser-induced diffusion requires meticulous cleaning to ensure a pristine surface. The process typically begins with the removal of organic contaminants and native oxides. A standard method for this is the RCA (Radio Corporation of America) clean, a two-step wet chemical process. The first step, SC-1 (Standard Clean 1), involves immersing the substrate in a solution of ammonium hydroxide (NH_4OH), hydrogen peroxide (H_2O_2), and deionized (DI) water at an elevated temperature, typically around 70-80°C. This solution effectively removes organic residues and particles from the surface. The substrate is then thoroughly rinsed with DI water. The second step, SC-2, uses a solution of hydrochloric acid (HCl), hydrogen peroxide (H_2O_2), and DI water, also at an elevated temperature. This step is crucial for removing metallic ions from the surface. Following another extensive DI water rinse, the substrate is ready for the final, critical step: removing the native oxide layer. This is accomplished by dipping the silicon wafer into a dilute solution of hydrofluoric acid (HF). This etches away the silicon dioxide, leaving a hydrogen-terminated surface that is less reactive and remains clean for a short period. The final rinse with DI water and subsequent nitrogen gas drying prepares a clean, oxide-free surface, which is essential for ensuring a direct, low-resistance interface between the metal contact and the silicon.

After the initial cleaning, the substrate is ready for the deposition of the metal and dopant layers required for laser-induced diffusion. The 1.5x1.5 cm dimensions are suitable for laboratory-scale experiments. The cleaned wafer is immediately transferred to a high-vacuum deposition chamber to prevent re-oxidation. A thin layer of the desired metal, such as nickel (Ni) or aluminum (Al), is deposited using a technique like electron-beam evaporation or sputtering. This metal layer serves as both the contact material and a medium for the dopant atoms to diffuse into the silicon. Often, a thin layer of a dopant-rich material is deposited alongside the metal or as a separate layer. For n-type silicon, common dopants include phosphorus (P) or arsenic (As). The thickness of these deposited layers is critical and typically in the range of a few nanometers to tens of nanometers. The wafer is then placed on a stage where it can be irradiated by the laser. A pulsed laser, such as an excimer laser or a frequency-doubled Nd:YAG laser, is directed at the specific areas where Ohmic contacts are desired. The laser parameters—power, pulse duration, and number of pulses—are carefully tuned to melt only the deposited films and a shallow, localized region of the silicon. This controlled melting allows the dopant atoms to rapidly diffuse and activate within the silicon lattice. The rapid solidification, in milliseconds, "freezes" the dopant atoms in place, creating a highly doped, low-resistance layer that forms the Ohmic contact. The localized nature of the laser annealing ensures that the bulk properties of the silicon substrate remain unaffected.

A Q-switched Coherent 7901 Nd:YAG laser system is commonly used for fabricating Ohmic contacts on silicon substrates via laser-induced diffusion due to its ability to deliver high-energy pulses in a very short duration. The wavelength is a critical parameter, with the fundamental wavelength typically being 1064 nm (in the infrared range), which silicon can absorb efficiently. The pulse duration is in the nanosecond (ns) range, usually between 5 to 10 ns. This short pulse width allows for rapid, localized heating of the surface, causing melting and dopant diffusion without significant heat transfer to the bulk of the silicon substrate. The laser fluence (energy per unit area) is a key parameter that must be carefully controlled to achieve optimal results. For silicon, typical fluences range from 1 to 25 J/cm^2, and finding the correct value is crucial; too low, and the surface won't melt sufficiently for diffusion; too high, and it can cause ablation, thermal stress, and defects like cracks. Finally, the repetition rate (the number of pulses per second) and the number of pulses applied to a single spot are also important for controlling the overall thermal budget and dopant concentration at the interface.

3. Results and Discussion

Figure (2) shows the variation of sheet resistance of the treated sample with the number of Q-switched Nd:YAG laser pulses, initially demonstrates a rapid and desirable decrease in resistance. This trend, particularly from 5 to approximately 50 pulses, is the direct result of the laser's localized energy delivery. Each high-intensity, short-duration pulse melts a thin surface layer of the silicon substrate and the deposited cobalt film. This process enables the rapid diffusion and activation of cobalt and dopant atoms, leading to the formation of a highly conductive cobalt silicide ($CoSi_2$) layer. The significant reduction in sheet resistance, from 4000 Ω/sq at 5 pulses to a minimum of around 500 Ω/sq near 50 pulses, is due to two primary factors: the low electrical resistivity of the newly formed silicide and a high concentration of electrically active dopants [39]. The steep negative slope of the curve in this region signifies a highly efficient process, where each successive pulse significantly improves the electrical characteristics of the contact, which is the primary objective of this fabrication method.

The most critical feature of this plot is the clear optimal processing window that it identifies. After reaching a minimum sheet resistance at approximately 50 pulses, the curve begins to turn upward, and the resistance increases with further laser pulses. This is a crucial piece of information for any fabrication process. The rise in resistance cannot be explained by a reduction in dopant concentration, as each pulse continues to drive dopants into the substrate. Instead, it is attributed to the creation of crystallographic defects within the silicon lattice [40]. The repeated, rapid heating and cooling cycles induce significant thermal stress, leading to the formation of defects such as dislocations and vacancies. These defects act as trapping and scattering centers for the charge carriers, which drastically reduces their mobility. The plot therefore highlights a competition between two opposing effects: the beneficial increase in carrier concentration from dopant activation and the detrimental decrease in carrier mobility from defect formation. Beyond 50 pulses, the negative impact of reduced carrier mobility outweighs the positive effect of increased concentration, causing the overall sheet resistance to rise and degrading the performance of the Ohmic contact. This figure serves as a powerful diagnostic tool, demonstrating that while laser processing is effective, it requires precise control of the pulse count to achieve optimal device performance and avoid irreparable damage to the silicon substrate.

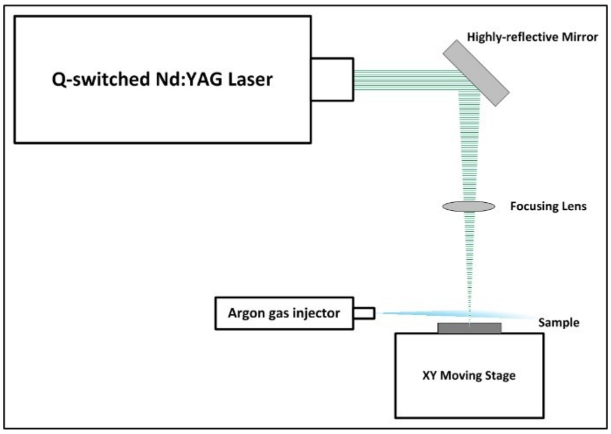

Fig. (1) Experimental setup of laser-induced diffusion and Q-switched Nd:YAG laser system used in this work

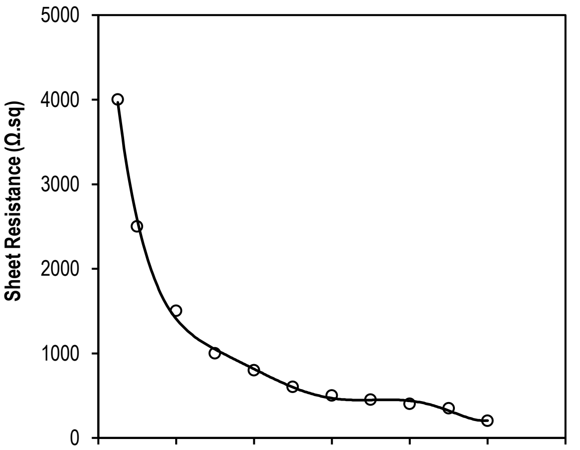

Fig. (2) Variation of sheet resistance of the treated samples with number of laser pulses

Figure (3) shows the variation of electrical conductivity of the treated sample with the number of laser pulses. The overall trend shows that conductivity generally increases with the number of pulses, which is the desired outcome. This is because each laser pulse provides the energy to melt a thin surface layer of the silicon, facilitating the diffusion and activation of dopant atoms and the formation of highly conductive cobalt silicide [41]. This process increases the free charge carrier concentration, which is directly proportional to electrical conductivity ($\sigma = qn\mu$). The curve's initial sharp rise, peaking around 10-15 pulses, signifies a highly efficient phase of dopant activation where the material rapidly transitions from a low-conductivity state to a more conductive one. This is the crucial first step in forming a functional Ohmic contact.

A deeper analysis reveals subtle but critical nonlinearities that have significant implications for process optimization. The plot shows a noticeable decrease in electrical conductivity between approximately 20 and 40 pulses. This behavior, which runs counter to the general trend, highlights the complex interplay of competing physical mechanisms. While additional pulses continue to increase the dopant concentration, they also induce thermal stress and generate crystallographic defects within the silicon lattice. These defects can act as scattering centers for the charge carriers, thereby reducing their mobility (μ). For a brief period between 20 and 40 pulses, the negative impact of reduced carrier mobility appears to slightly outweigh the positive effect of increased carrier concentration, causing the overall conductivity to dip. However, after 40 pulses, the conductivity begins to rise sharply again, suggesting that a different, more powerful mechanism—perhaps a more complete phase transition of the cobalt silicide or a different dopant diffusion pathway—takes over. This final increase indicates that a high number of pulses (e.g., 80-90) is necessary to achieve the maximum possible conductivity for this specific fabrication process. The non-linear behavior of this figure demonstrates that simple, monotonic increases in laser pulses do not guarantee improved performance and underscores the critical need for meticulous process control to avoid operating in a suboptimal range.

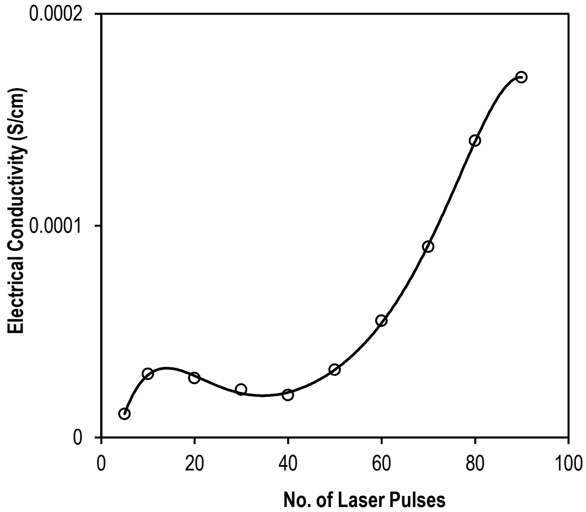

Fig. (3) Variation of electrical conductivity of the treated samples with number of laser pulses

Figure (4) represents an Arrhenius plot, which is a powerful tool used in physical chemistry and materials science to model the temperature dependence of reaction rates. This figure displays the remaining cobalt on the surface of the treated sample as a function of the inverse of the absolute temperature (1/T). This linear relationship confirms that the process governing the consumption of cobalt on the silicon surface follows an exponential Arrhenius dependence. In the context of microelectronics, this process is not simple desorption, but rather the thermally-activated reaction between the deposited cobalt and the underlying silicon substrate to form a more stable compound, specifically $CoSi_2$ [42]. This formation is the key step in creating a low-resistance Ohmic contact. The linear trend in this figure provides critical insights into the kinetics of this reaction. The negative slope of the line is directly proportional to the activation energy (E_a) of the silicide formation process. A steeper slope would indicate a higher activation energy, meaning the reaction requires more thermal energy to proceed and is therefore more sensitive to temperature changes. The plot clearly shows that as the temperature increases (i.e., 1/T decreases), the amount of remaining cobalt decreases. This is the expected behavior: at higher temperatures, the atoms have more kinetic energy, leading to a faster reaction rate and more complete formation of the silicide layer within a given time.

This figure has a profound significance for semiconductor manufacturing. By accurately measuring the slope and calculating the activation energy, engineers can precisely determine the thermal budget required for forming reliable Ohmic contacts. This allows them to move beyond a trial-and-error approach and establish a highly predictable and reproducible process, typically using rapid thermal annealing (RTA) [43]. The figure enables them to select the optimal annealing temperature and time to ensure the cobalt fully reacts to form $CoSi_2$ without overheating the wafer. Overheating could lead to "silicide spiking," where the silicide penetrates too deeply into the silicon, potentially shorting out shallow junctions—a critical failure mode in scaled down transistors. However, the figure also has some limitations. For a truly deep analysis, one would want to see error bars on the data points to assess the reliability of the linear fit. Additionally, the y-axis, labeled remaining cobalt on silicon surface, lacks specific units. While its logarithmic scale is correct for the Arrhenius model, knowing whether the measurement is in terms of thickness, atomic concentration, or another metric would provide a more complete quantitative understanding. Despite these minor critiques, the plot remains an invaluable diagnostic tool. Its elegant linear relationship encapsulates the fundamental trade-off in Ohmic contact fabrication: the need for sufficient thermal energy to drive the silicide formation while avoiding excessive heat that could damage the delicate underlying device structures [44].

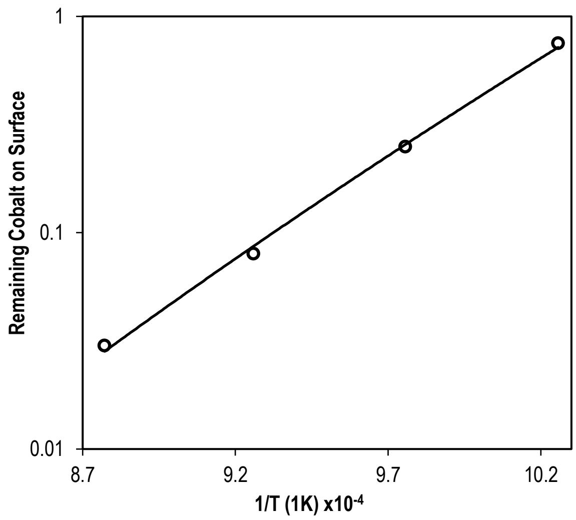

Fig. (4) Variation of cobalt remaining on the surface of silicon sample irradiated with laser pulses as a function of reciprocal temperature

4. Conclusions

In conclusion, laser-induced diffusion is a highly effective method for fabricating cobalt Ohmic contacts on n-type silicon. The process demonstrates a clear trade-off between the beneficial effects of dopant activation and the detrimental formation of crystallographic defects. While a certain number of laser pulses is necessary to achieve a low-resistance contact by forming cobalt silicide, exceeding an optimal pulse count can degrade performance by reducing carrier mobility. Therefore, meticulous control of laser parameters is essential to achieve a highly predictable, low-resistance Ohmic contact while avoiding device damage.

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